ADA

ENGINE DURABILITY EVALUATION USING SYNTHETIC FUEL, CATERPILLAR C7 ENGINE

INTERIM REPORT
TFLRF No. 391

by
Matthew E. Schulman
Edwin A. Frame

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. DAAE-07-99-C-L053 (Task IX, WD23)

October 2008

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14. ABSTRACT
Fischer-Tropsch (F-T) synthetic fuel is considered a "clean" fuel because it typically will contain no sulfur or aromatics, but these differences from petroleum fuel (JP-8) may translate to some degree of change in equipment/engine performance in regards to power output, fuel ignition and combustibility, fuel system sealing, and fuel lubricity. A Caterpillar C7 engine was used to compare operations between JP-8 and F-T fuel. The engine was measured dimensionally, broken-in, and full-load engine performance was measured with the synthetic fuel and also JP-8, DF-2 and a 1:1 blend of S-8/JP-8. Then, the synthetic fuel was used in conducting a 420-hour endurance test cycle for comparison with same test conducted previously for JP-8. Data collection included daily oil sample analysis, post-test full-load performance, pre- and post-test engine measurements, and interim- and post-test analysis for wear and deposits. In the 420-hour test cycle, the synthetic fuel performed similarly to JP-8 in most regards.

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EXECUTIVE SUMMARY

Problems and Objectives

Fischer-Tropsch (FT) synthetic fuel can be produced from various resources such as natural gas, coal, biomass, or other carbon-containing streams. In each case, the starting resource must first be converted to synthesis gas consisting of mainly carbon monoxide and hydrogen. From there, this gas can then be converted to long-chain liquid hydrocarbons via the FT reaction. A commonly used acronym for conversion of synthesis gas to these FT-derived liquid hydrocarbons is "GTL", although some use this acronym to mean the conversion of natural gas to FT-derived liquid hydrocarbons; similarly, the acronyms commonly used for coal and biomass are "CTL" and "BTL", respectively. FT-derived fuels will contain no sulfur, and when a low-temperature FT reaction using a cobalt-based catalyst is used, the fuels will also contain no aromatic compounds. On the other hand, petroleum-derived fuels do typically contain both sulfur and aromatics; it is these differences between the "clean" FT fuels and petroleum fuels that raise some issues, particularly with respect to: (1) adequate lubrication of some engine fuel systems and other equipment; and (2) maintaining enough seal swell to avoid leakage when fuel systems are switched between petroleum and synthetic fuels. The objective of this program was to develop comparative data of the performance.

Importance of Project

The Department of Defense has shown a keen interest in synthetic fuels as alternative fuels because their domestic production and use can lessen dependence on foreign crude oil (petroleum), while also reducing tailpipe exhaust emissions due to their cleaner-burning nature. The acceptable performance of synthetic fuel in a key engine such as the Caterpillar C7 found in the Family of Medium Tactical Vehicles is an important and necessary step in determining the viability of the use of a synthetic alternative fuel.

Technical Approach

For each test, a Caterpillar C7 engine was disassembled, measured and reassembled, then installed in a test cell with appropriate control devices, instrumentation and ancillary equipment. The engine was operated for several hours as a break-in, then full-load engine performance was

measured using the synthetic fuel and several others for comparison. A 14-hour test cycle consisting of periods of operation at rated power and idle was conducted for a total of 420 hours over a period of weeks, with oil samples taken and analyzed daily. Full-load performance was re-measured, before the engines were disassembled for measurement, and analysis of wear and deposits.

The report includes sufficient detail of the test setup to repeat the testing if desired. Details of the test procedure, as well as any deviations from that procedure, are documented. Each test includes graphs presenting the results of oil chemical analysis and wear metal tests.

Five key oil characteristics are tracked through the progress of each test, with comparison among the tests. Similarly, the levels of several wear metals are presented for comparison among the tests. Finally, several post-test wear evaluations are included.

Accomplishments

Despite the elevated air, coolant, fuel and oil temperatures, the engine completed the 420-hour test cycle. The synthetic fuel performed similarly to JP-8 in most regards.

Military Impact

As the military moves forward to explore alternative fuel sources to reduce dependency on petroleum fuel, non-conventionally-produced fuels increase in viability. The synthetic fuel used in these evaluations is one such type fuel produced from a synthesis process developed early in the last century known as Fischer-Tropsch. Results of successful military equipment operability provided in this report play an important role in establishing that synthetic fuel is suitable for use. This, in turn, provides the possibility to convert U.S. military ground equipment to use an alternative hydrocarbon fuel, thus increasing the energy security of the U.S. Military.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period January 2007 through October 2007 under Contract No. DAAE-07-99-C-L053. The U.S. Army Tank Automotive RD&E Center (TARDEC), Force Projection Technologies, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSRD-TAR-D/MS110) served as the TARDEC contracting officer's technical representative. Ms. Pat Muzzell and Mr. Eric Sattler of the U.S. Army National Automotive Center served as project technical monitors.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by Rebecca Emmot.

TABLE OF CONTENTS

LIST OF TABLES

<u>Table</u> **<u>Page</u>**

LIST OF FIGURES

<u>Figure</u> **<u>Page</u>**

ACRONYMS AND ABBREVIATIONS

° C	degrees Centigrade
° F	degrees Fahrenheit
Abs.	absorbance
API	American Petroleum Institute
ASTM	ASTM International
bhp	brake horsepower
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
CI	corrosion inhibitor
cm	centimeter
CO	carbon monoxide

ACRONYMS AND ABBREVIATIONS (continued)

CO_2	carbon dioxide
CRC	Coordinating Research Council
cSt	centiStoke
DTIC	Defense Technical Information Center
FMTV	Family of Medium Tactical Vehicles
ft	foot
FT *or* F-T	Fischer-Tropsch
FTIR	Fourier transform infrared
FTP	fuel transfer pump
HC	hydrocarbon(s)
HEP	high-pressure oil pump
HP *or* hp	horsepower
hr	hour
ICP	inductively-coupled plasma
in	inch
in^3	cubic inch
KOH	potassium hydroxide
kW	kilowatt
L	liter
lb	pound
lb_f	pound (force)
lb_m	pound (mass)
m	meter
mg	milligram
mm	millimeter
N	Newton
NO_X	oxides of nitrogen
O_2	oxygen
OEM	original equipment manufacturer
ppm	parts per million
psi	pounds per square inch
psiA	pounds per square inch, absolute
psiG	pounds per square inch, gauge
rpm	rotation(s) per minute
SAE	Society of Automotive Engineers
SwRI®	Southwest Research Institute®
TACOM	Tank Automotive and Armaments Command
TAN	total acid number
TARDEC	Tank Automotive RD&E Center
TBN	total base number
TFLRF	TARDEC Fuel and Lubricants Research Facility
TGA	thermogravimetric analysis
TWV	tactical wheeled vehicle
WD	work directive

1.0 INTRODUCTION AND BACKGROUND

Fischer-Tropsch (FT) process synthetic fuels, first produced in 1927, were used by WWII Germany and by South Africa during their embargoed period, to overcome petroleum shortages. Synthetic JP-8 is a clean fuel that contains no sulfur or aromatics, but has historically cost too much to compete with petroleum fuel. Since the mid-1990s, the world's major energy companies have begun developing updated FT processes that are less expensive to build and operate. The goal is to produce a sulfur-free product that helps meet air quality requirements from the conversion of various non-petroleum resources such as natural gas, coal, biomass, or other carbonaceous sources. Synthetic fuel chemistry can differ significantly from that of petroleum fuels since modern, low-temperature reaction FT synthetic fuels are free of aromatic and sulfur compounds. These differences may impact performance of equipment, such as: (1) fuel volumetric energy density and resultant power produced; (2) fuel cetane rating and the resultant ignition and combustion behavior; (3) fuel lubricity and adequate lubrication of some engine fuel systems and other equipment; and (4) fuel solvency and impacts on some elastomers in maintaining enough seal swell to avoid leakage when fuel systems are switched between petroleum and synthetic fuels. Some of these possible performance aspects are investigated in this project.

This project seeks to compare engine performance using a Fischer-Tropsch (S-8) fuel over a high-temperature endurance cycle, to performance observed under similar conditions using petroleum-based JP-8 fuel.

2.0 EVALUATION DETAILS

2.1 Test Configuration

Testing was conducted with a Caterpillar C7 engine, in the configuration used in the Family of Medium Tactical Vehicles (FMTV) variants. Prior to testing, the engine was disassembled, measured for pre-test clearances and specifications, and re-assembled following the guidelines in the Caterpillar factory service manual. Engine specifications are presented in Table 1. The engine was installed in building 99, cell 4, with systems to monitor and control the test. Figure 1 shows the Caterpillar C7 engine installed in the test cell:

Table 1. Engine Specifications

Bore	4.33 inch ~ 110 mm
Stroke	5.00 inch ~ 127 mm
Displacement	441 in^3 ~ 7.2 L
Rated Power	330 HP ~ 246 kW @ 2400 rpm
Rated Load	860 ft·lb_f ~ 1166 N·m @ 1440 rpm
Serial Number	FMM03100

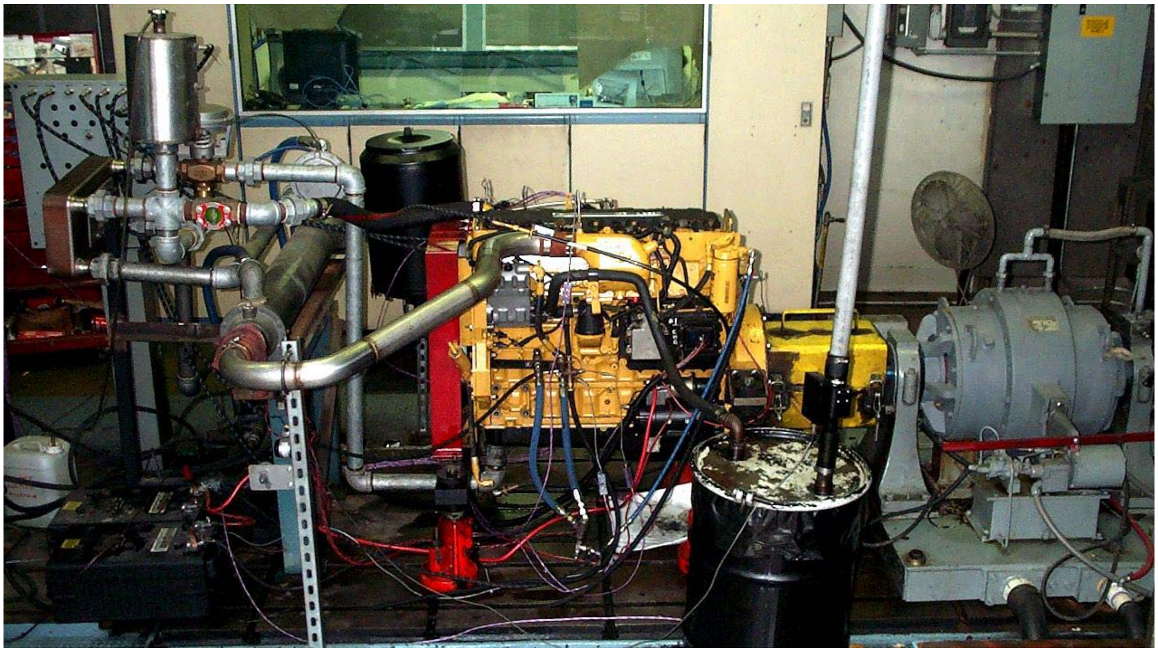


Figure 1. Caterpillar C7 Engine Installed for Testing

- The engine is instrumented to measure a range of engine operating parameters, temperature and pressures. A SwRI-proprietary PRISM system controls the engine and associated test equipment and acquires and logs test data. A complete list of recoded data types is included as Appendix A.

- An absorbing dynamometer system limits engine speed. The factory engine controller regulates engine load, in response to a signal produced by the cell controller to simulate the OEM accelerator pedal output.

- Laboratory heat exchangers are installed to regulate coolant and inlet air temperature in place of the engine radiator and intercooler. Oil temperature is controlled indirectly by the coolant, via an oil-to-coolant heat exchanger integral to the engine.

- An OEM-style air filter and housing and appropriate ducting is installed on the engine. Inlet air is drawn from inside the cell through the building ventilation system, at ambient conditions.

- Engine exhaust is drawn from the engine by a large fan and discharged above the building. A butterfly valve to control back-pressure and probes to sample smoke and gaseous emissions are installed in the exhaust stream.

- Crankcase blowby fumes are ducted into a drum where most of the entrained oil is captured, then the gases are vented to the cell air through a flow meter to measure the blowby rate.

- Fuel is supplied to the engine at ambient pressure from a tank, which also receives fuel recirculated from the engine. Fuel is supplied to the tank as necessary to maintain a constant level. The incoming fuel flow rate is measured by a Micromotion mass flow rate system. A heat exchanger is installed and controlled to prevent the fuel inlet from exceeding a set temperature. A new OEM fuel filter is installed before each test.

- Piping is installed to enable periodic oil sampling. A tube is mounted on the front engine case for oil additions.

- Engine coolant is a 60/40 blend of Prestone II (ethylene glycol) antifreeze and de-ionized water.

- The engine is lubricated with Army Reference Oil, MIL-PRF-2104G, SAE grade 15W40. The properties of this oil are shown in Appendix B. A new OEM oil filter is installed with each oil change.

2.2 Test Operation

2.2.1 Engine Run-In

Before beginning the test cycle, the newly-rebuilt engine undergoes a break-in procedure lasting approximately five hours, during which the engine repeatedly cycles through a variety of operating conditions, including engine speeds from idle to 2400 rpm (rated speed), and engine loads from idle (no load) to peak torque.

2.2.2 Pretest Engine Performance Checks

Engine performance was measured prior to endurance testing. The engine was set to run at full power at each of ten engine speeds, including the peak torque speed, 1440 rpm; the rated speed, 2400 rpm; and the governed speed, 2800 rpm. The engine operated at each speed until conditions stabilized, after which the full range of data available was recorded, including gaseous emissions and smoke. At the completion of this testing, the engine oil was drained and replaced with a carefully-weighed quantity of new oil. A new oil filter was installed.

2.2.3 Test Cycle

The test cycle is based on the Army and Coordinating Research Council 210-hour Tactical Wheeled Vehicle (TWV) procedure that simulates 20,000 miles of proving ground operation [1]. The cycle as defined includes 15 days of operation, each comprising five two-hour periods of rated power operation, alternated with four one-hour periods of idle operation, for a total of 14 hours per test day. The remaining 10 hours of each test day are engine-off “soak” time, during which the engine system cools to ambient conditions, The soak time does not contribute to the 210-hour total. Test time is accumulated only during the running segment. The test continues for 210 hours or until the oil degrades to the point of oil condemnation limits, whichever occurs first.

For the purposes of this testing, the standard 210-hour TWV Cycle was extended to a total of 420 hours (which simulates 40,000 miles of proving ground operation). Coolant, oil, fuel and inlet air temperatures are elevated to simulate desert warfare conditions, chosen to achieve and maintain oil sump temperature at 260° F during rated power operation. The test using Fischer-Tropsch fuel used the 14-hour daily test cycle described. The Baseline test was conducted under accelerated conditions for a different work directive, in which the daily test cycle was 20 hours (seven two-hour periods of rated operation, alternated with six one-hour periods of idle operation), followed by only four hours of "soak" time, in order to complete the doubled test hour duration in only twenty-one days of testing.

Engine oil is sampled for analysis every 14 hours of test operation. Larger samples are taken at 70-hour intervals for more detailed tests. After each sample, a quantity of new oil approximately equal in weight to the sample removed is added to the engine. This makeup oil is not included in the oil consumption calculations.

Gaseous emissions and smoke are measured once per 14 hours of test operation, approximately once per day, while the engine is running at rated power.

During the daily 10-hour shutdown, the engine is inspected for loose fittings, leaks and any other visible sign of a current or impending problem. The oil level is checked and recorded 20 minutes into the soak period. If the oil is below the full mark, a quantity of new oil sufficient to restore the oil level to the full mark is measured, recorded and added.

2.2.4 Post-Test Engine Performance Checks

Following completion of the 420-hour test, engine performance is measured in exactly the same way as before testing, with the goal of comparing the two measurements.

2.2.5 Post-Test Measurements, Ratings, and Photographs

Upon completion of all testing, the engine is removed from the test cell and disassembled to determine and quantify wear effects and engine deposit ratings. Post-test measurements of the same features measured prior to testing are documented. Many internal engine parts are photographed and rated, which in some cases requires destruction of those parts. The measurements and photographs are included in the test report, attached as Appendix E (baseline, JP-8 Fuel) and Appendix G (S-8 fuel).

3.0 DISCUSSION OF TESTS

3.1 Test 1: Baseline (JP-8)

The first test, conducted on another work directive [2], established a reference standard for later tests. For this test, the engine operated on petroleum-based JP-8 fuel, representative properties of which are shown in Appendix D. No AL code was given to the test fuel because multiple shipments of JP-8 from a single source (age refinery) were used during this testing.

A detailed test report is attached as Appendix E. The engine completed the 420 hours of testing with some oil degradation, but not to a degree warranting an early end of test. Testing was conducted as described in Section 2 above, with the following exceptions:

- Daily operation for the Baseline test lasted for 20 hours rather than 14, consisting instead of seven (rather than five) two-hour periods of operation at rated power, alternated with six (rather than four) one-hour periods of operation at low idle. The “soak” period, therefore, lasted only four hours, rather than ten.

- There were several sudden engine shutdowns caused by cell and dynamometer controller problems. In each case the problem was diagnosed and corrected, then the engine was restarted and returned to the cycle.

- Two fuel injectors failed and were replaced on separate occasions: #2 at 259 hours, and #6 at 335 hours. In the process of replacing the first one, the adjoining injector for cylinder 3 was accidentally damaged, so it was replaced as well.

3.2 Test 2: Synthetic Fuel (S-8)

The second test was conducted similarly to the earlier Baseline test, toward the goal of comparing the tests' results. New engine rebuild components installed for this test included all fuel injectors, to eliminate the possibility of prior damage affecting the test results, and because the Baseline test also started with a set of new injectors. For this test, the engine operated on synthetic S-8 fuel (AL-27755), representative properties of which are shown in Appendix C. It was determined that additional corrosion inhibitor/lubricity improver additive would be added to the bulk shipment of S-8 fuel, to increase the total CI content to 22.5 ppm.

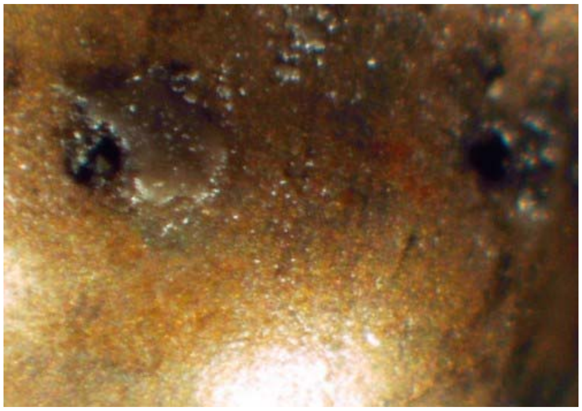
Prior to beginning the scheduled 420-hour endurance test, the Caterpillar C7 engine performed full load power curves and exhaust emissions for the following fuels: S-8 (AL-27755); DF-2 (AL-27621); JP-8 (AGE); and a 50/50% blend (by volume) of S-8/JP-8 (AL-27735). Appendix F contains the inspection properties for the DF-2, JP-8, and 50/50% vol blend. The 420-hour endurance test was then conducted only for the S-8 fuel (AL-27755).

A detailed report on the endurance testing is attached as Appendix G. The engine completed the 420 hours of testing with some oil degradation, but not to a degree warranting an early end of test. Testing was conducted as described in Section 2, with the following exceptions:

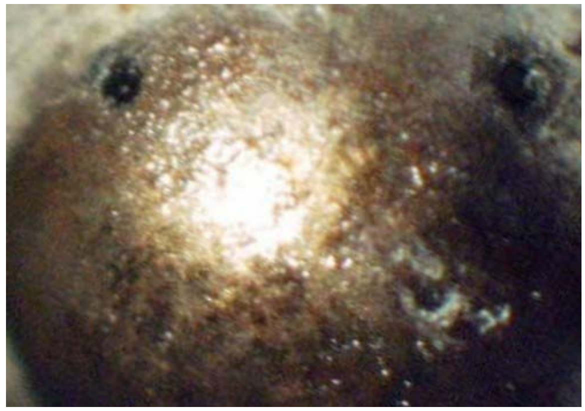
- After approximately 132.6 hours of operation, cell safeties recognized and reacted appropriately to an external cooling failure. After this was corrected, the engine was restarted and warmed up to prepare it for resumption of testing. Shortly after reaching operating temperature and resuming testing, a bolt between the engine's fuel transfer pump (FTP) and high-pressure oil pump (HEP) failed. This allowed an oil seal to fail, causing the engine to pump its lubricating oil onto the cell floor and causing an engine shutdown. The complete assembly of HEP and FTP was removed from the engine for failure analysis. Two small bolts were found to have failed in the plane mating the two pumps. It is likely that the failure of one caused additional stress on the second, causing its failure in turn. No root cause was apparent other than the failed bolts. The FTP was reassembled to the HEP with three new bolts of equivalent size and type from stock on hand. The pump assembly was reinstalled on the engine, 16 liters of new oil were added to bring the oil back to full, the engine was warmed up and resumed testing. The failure caused a testing delay of one day.

- At 140.0 test hours, as the engine performed a part of the cycle when it idles briefly before shutting down for one of the 10-hour 'soak' periods, the failure recurred. The presence of an operator in the test cell at the time and his quick reaction hastened the shutdown on this incident, so less oil was lost, though still more than half of the total. The pump assembly was again removed for analysis and repair. Again, two of the same three small bolts had failed, though in this instance, one failed between the threaded portion and the head, rather than in the plane mating the two pumps. Caterpillar technical representatives indicated that the failures were a known issue, likely not related to the high temperatures or fuel involved in this testing. Cat provided a replacement pump and a procedure for reassembling the FTP and HEP. SwRI technicians followed these instructions, reassembled the pumps and reinstalled the assembly on the engine. The failed HEP, bolts and seals were returned to Caterpillar for analysis, and data describing the failures and operating conditions were provided. The engine was recharged with approximately 13 liters of new oil before resuming testing. The failure caused a testing delay of two days. The engine operated normally through the end of testing without further incident.

- Starting after approximately 221.9 hours of testing, the exhaust temperature of cylinder 5 started to fluctuate at idle, then to fall. Diagnostic tests indicated a hydraulic or mechanical (not electrical) failure of that cylinder’s fuel injector, though only at idle conditions – the performance of cylinder 5 at rated power conditions did not change during this period. The injector was replaced with a new injector, and the test resumed with cylinder 5 exhaust temperatures back in normal range at all conditions. While the engine was shut down for the injector change, another injector was also removed, from an adjoining cylinder, to allow visual comparison of deposits between that working injector and the malfunctioning injector. Some deposits were observed on both injectors (see Figure 2 below), but not apparently to an extent that prevented injection – an observation borne out by the fact that the ‘failed’ injector continued to deliver fuel normally at rated conditions.



Injector 4 (working correctly)



Injector 5 (not injecting at idle)

Figure 2. Injector Nozzle Deposits

4.0 DISCUSSION OF RESULTS

4.1 Engine Performance Comparison

Table 2 presents a comparison of engine performance parameters, averaged based on all data acquired while the engine performed endurance testing. All of these measurements are within normal variation for this type of engine and the test setup, with the exception of the 50% greater average oil consumption in the S-8 test. The two unscheduled additions of new oil were assumed to be equal to the quantity lost accidentally, so were not considered in calculating the total oil consumption. Fresh oil has volatile components that are typically lost as the oil is heated the first time. The increased oil consumption in the S-8 test likely resulted from their loss after the additions of new oil previously discussed. Oil consumption was similarly higher in other tests in which new oil was periodically or continuously added to the engine.

Table 2. Test Parameters Summary

Parameter	unit	Baseline	S-8
Overall Average Oil Consumption (net)	lb_m/hr	0.063	0.098
Rated Average Oil Sump Temperature	°F	258.2	259.6
Rated Average Coolant Outlet Temperature	°F	217.5	217.1
Rated Average Air Intake Manifold Temperature	°F	140.5	140.0
Rated Average Fuel Inlet Temperature	°F	117.7	121.5
Rated Average BSFC	lb_m/BHP·hr	0.360	0.357

Figure 3 plots the maximum power produced by the engine prior to endurance testing with each of four different fuels, in (approximately) 200-rpm increments from 1000 rpm through 2800 rpm. The engine produced approximately 6% more power when fueled with DF-2 than with JP-8, S-8, or the blend of the two, all of which performed similarly to each other. It should be noted that the power and emissions characteristics of this engine were likely developed using fuel similar to the DF-2 tested, so an engine calibrated for one of the other fuels might produce more favorable results.

Figure 4 is similar to Figure 3, except that the information depicted was measured after the endurance testing, with the same four fuels under similar conditions for comparison. The scaling, line types and colors are identical to Figure 3, again to facilitate comparison between the two. Table 3, following Figures 3 and 4, summarizes some of the performance measurements. Generally speaking, the engine produced less peak power with all fuels following the endurance testing. It produced the most power and used the most fuel with DF-2 under nearly all conditions, though the power offset was less following endurance cycling. The engine fuel consumption increased fairly uniformly for all fuels.

Table 3. Test Parameters Summary

Fuel	Maximum Power Output [HP]						Brake-Specific Fuel Consumption (BSFC) [lb_m/HP·hr]					
	1440 rpm (Peak Torque Speed)			2400 rpm (Rated Power Speed)			1440 rpm (Peak Torque Speed)			2400 rpm (Rated Power Speed)		
	Before Test	After Test	% Change	Before Test	After Test	% Change	Before Test	After Test	% Change	Before Test	After Test	% Change
DF-2	224.0	212.9	- 5.0	319.2	304.5	- 4.6	0.350	0.363	+ 3.7	0.363	0.374	+ 3.0
JP-8	203.4	210.1	+ 3.3	302.2	299.0	- 1.1	0.342	0.352	+ 2.9	0.354	0.361	+ 2.0
S-8/JP-8 Blend	198.3	201.8	+ 1.8	299.3	296.1	- 1.1	0.353	0.363	+ 2.8	0.352	0.358	+ 1.7
S-8	200.6	195.5	- 2.5	302.5	293.9	- 2.8	0.340	0.349	+ 2.6	0.349	0.354	+ 1.4

Figure 3. Caterpillar C7 Engine Full Load Power Before Endurance Testing

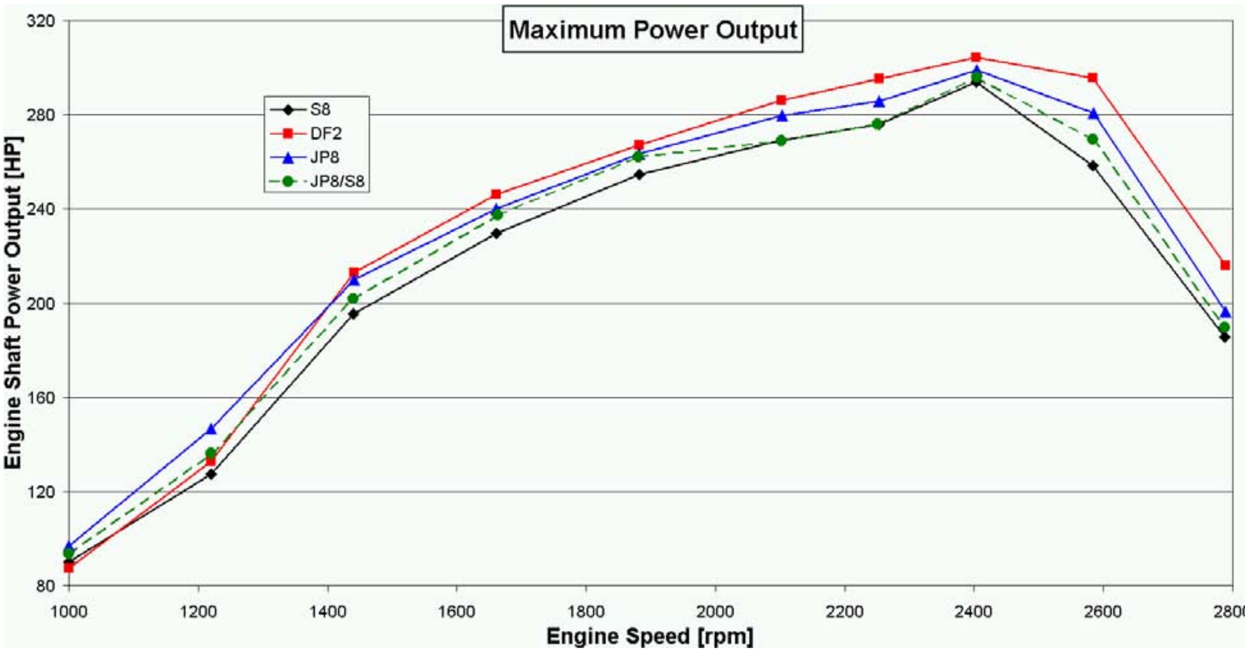


Figure 4. Caterpillar C7 Engine Full Load Power After Endurance Testing

4.2 Exhaust Emissions Comparison

Figures 5 through 9 present plots of exhaust emissions measurements from 1000 RPM through 2800 RPM in (approximately) 200-rpm increments. Line types and colors are common to all graphs, as is the legend in Figure 5.

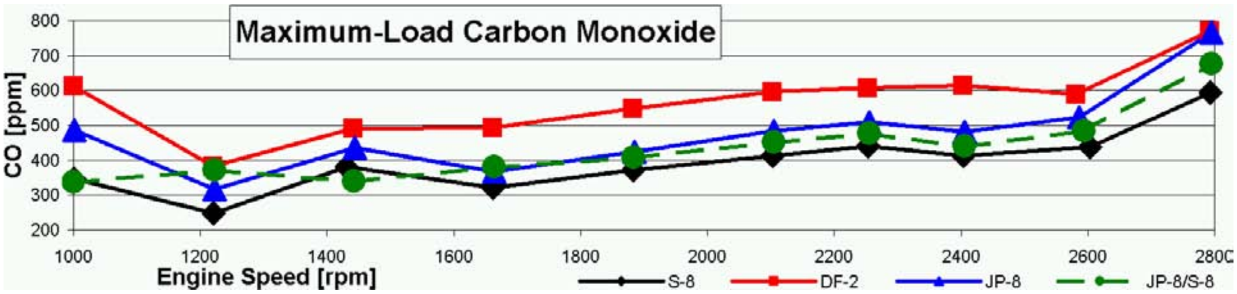


Figure 5. Caterpillar C7 Engine Full Load Carbon Monoxide Emission

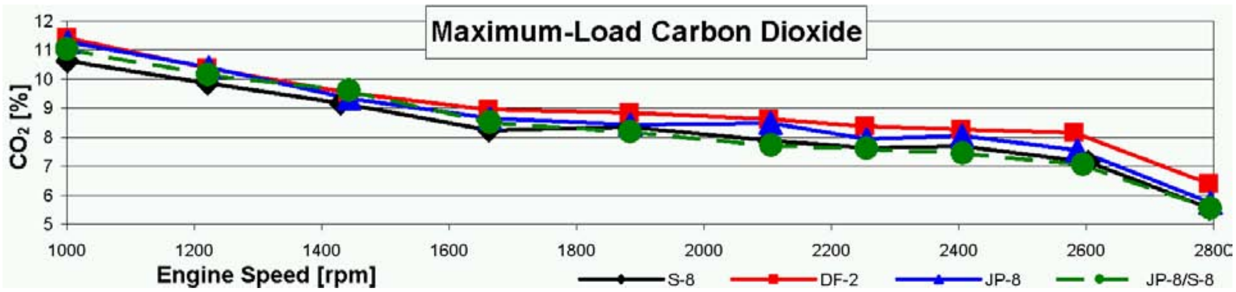


Figure 6. Caterpillar C7 Engine Full Load Carbon Dioxide Emission

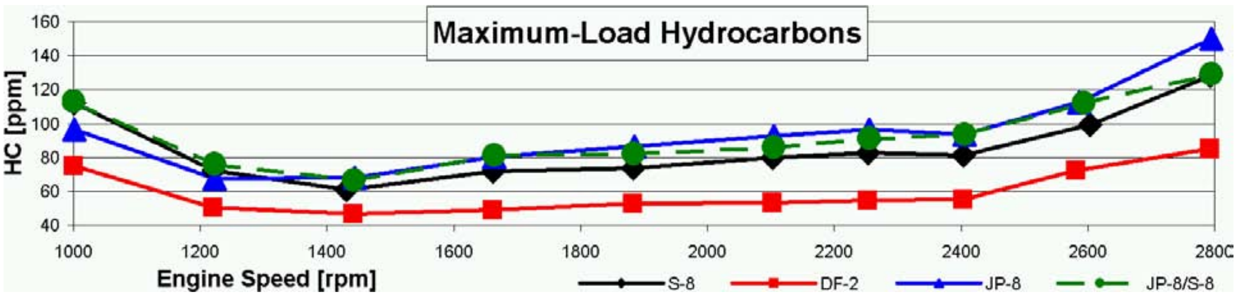


Figure 7. Caterpillar C7 Engine Full Load Hydrocarbon Emission

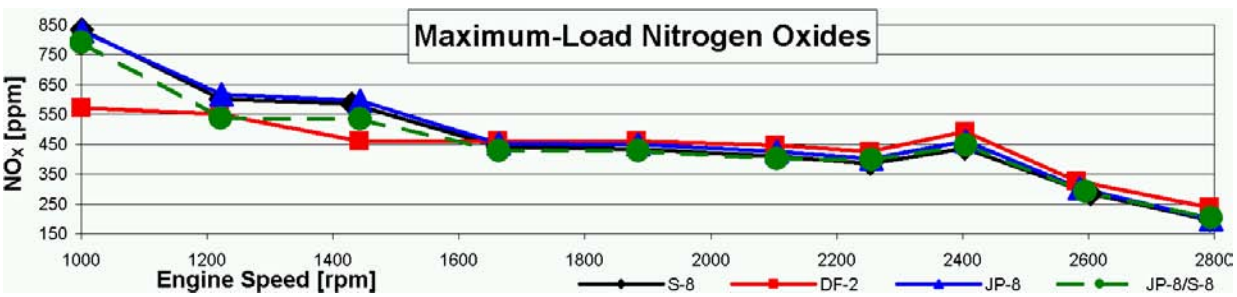


Figure 8. Caterpillar C7 Engine Full Load Nitrogen Oxides Emission

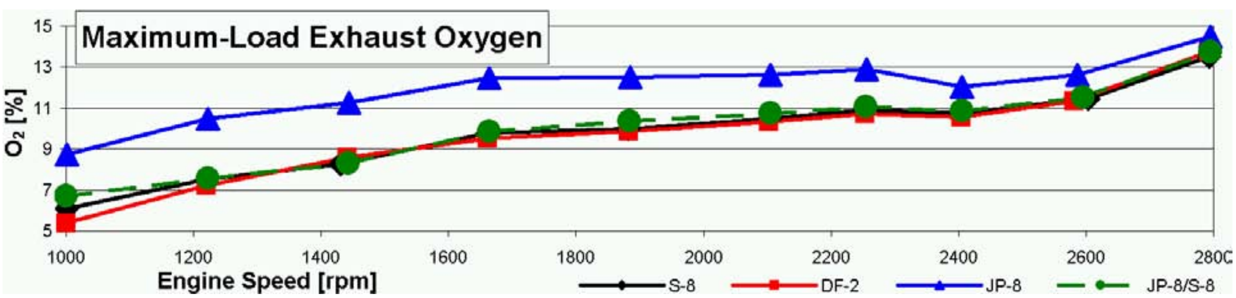


Figure 9. Caterpillar C7 Engine Full Load Exhaust Oxygen Concentration

As is apparent in Figure 5, the DF-2 produced an average of 20% more CO than did JP-8 under similar conditions; the S-8 produced about 16% less. Predictably, most data for the S-8/JP-8 blend fall between those from JP-8 and S-8.

The carbon dioxide measurements graphed in Figure 6 compare similarly, though the differences are smaller in relative terms. DF-2 produced about 4% more CO_2 than JP-8, S-8 produced about 4% less than JP-8, and the results with the blend were again between those from JP-8 and S-8.

Figure 7 shows the same trend among the HC results for the S-8, JP-8 and blend fuels, but the DF-2 is much lower. S-8 produced about 6% less hydrocarbons than JP-8, while the DF-2 produced less than two-thirds as much – a 36% reduction on average.

There is little difference among the nitrogen oxides results in Figure 8, though the separation of the DF-2 results from the others at lower speed may indicate cooler combustion – possibly resulting from quicker, therefore earlier, ignition – with this fuel under those conditions.

In Figure 9, the cause of the notably higher exhaust oxygen concentration from the JP-8 test is not clear. In previous C7 testing (WD 39), JP-8 at 2400 rpm fuel load averaged 10.28%, O_2 in the exhaust. This is also in the current test with JP-8. This may be related to engine to engine variation. In the current test, the engine produced power, efficiency and emissions results similar to the other runs, while running at similar temperatures, pressures, flow rates, etc. Although it would seem to be some effect resulting from the chemistry of the fuel itself, were that so, the result from running the S-8/JP-8 blend should be separated from the others. Although the oxygen concentration measurement instrument was calibrated successfully before and after the run, it does not agree with other data acquired under similar conditions with the same fuel. It would be advisable therefore not to draw conclusions from the O_2 data.

4.3 Oil Chemical Analyses

Graphs presented in this section depicting similar measurements share consistent colors, line types, scaling and other characteristics wherever possible, to facilitate comparison among graphs. Figures 10–16 compare results of periodic wear metal and oil chemical analysis tests between the baseline and the S-8 test conducted under this effort.. Vertical lines on Figures 10-15 indicate the test time at which a substantial portion of the engine oil was lost and replaced with new oil during the S-8 test.

4.3.1 Total Acid Number (TAN)

Figure 10 presents the overlaid results of oil testing to determine the oil acid number in each periodic sample of the tests previously described.

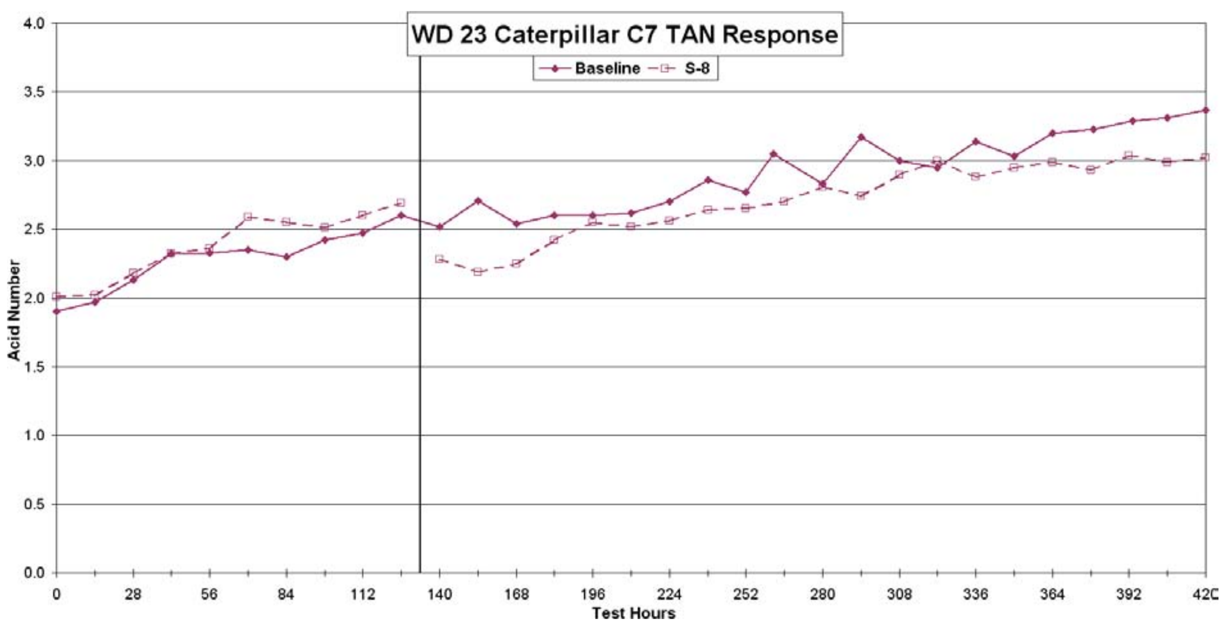


Figure 10. Oil Total Acid Number Test Results, Synthetic Fuel vs Baseline

- Some measurement inaccuracy is evinced in the oscillation of some of the plots, but both follow the generally-increasing trend expected.

- It is desirable for the TAN not to exceed 5. No result in this testing approached that level.

- A drop in the TAN results between the S-8 samples at 126 and 140 hours corresponds to the oil losses previously described.

- The TAN results for this test closely follow those from the Baseline test.

4.3.2 Total Base Number (TBN)

Figure 11 presents the overlaid results of oil testing to determine the oil base number in each periodic sample of the tests previously described.

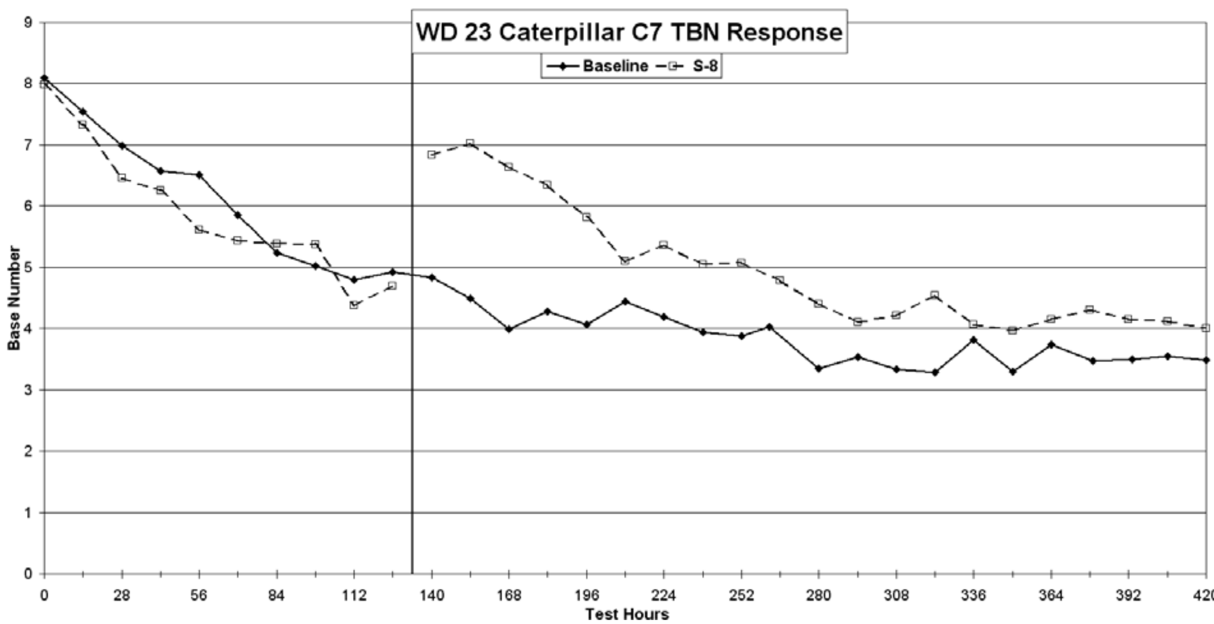


Figure 11. Oil Total Base Number Test Results, Synthetic Fuel vs Baseline

- Some measurement inaccuracy is evinced in the oscillation of some of the plots, but both follow the generally-decreasing trend expected.

- It is desirable for the TBN to remain above 2, and not fall below half of the value for new oil—approximately 4 in this case, half of the initial value of 8.1. Neither of the tests approached TBN=2. The Baseline test TBN did fall below 4 at 168 hours, and remained below 4 after 266 hours. Oil losses during the S-8 test prior to the 140-hour sample prevent these results from showing what the TBN result would have been, but based on the observed trend, it would likely have remained at or near 4 for the remainder of the test.

- Based on the results prior to the oil loss that occurred at 132 hours, the S-8 test results appear to be following the Baseline result.

4.3.3 Oxidation

Figure 12 presents the overlaid results of oil oxidation testing, as determined by FTIR, in each periodic sample of the tests previously described.

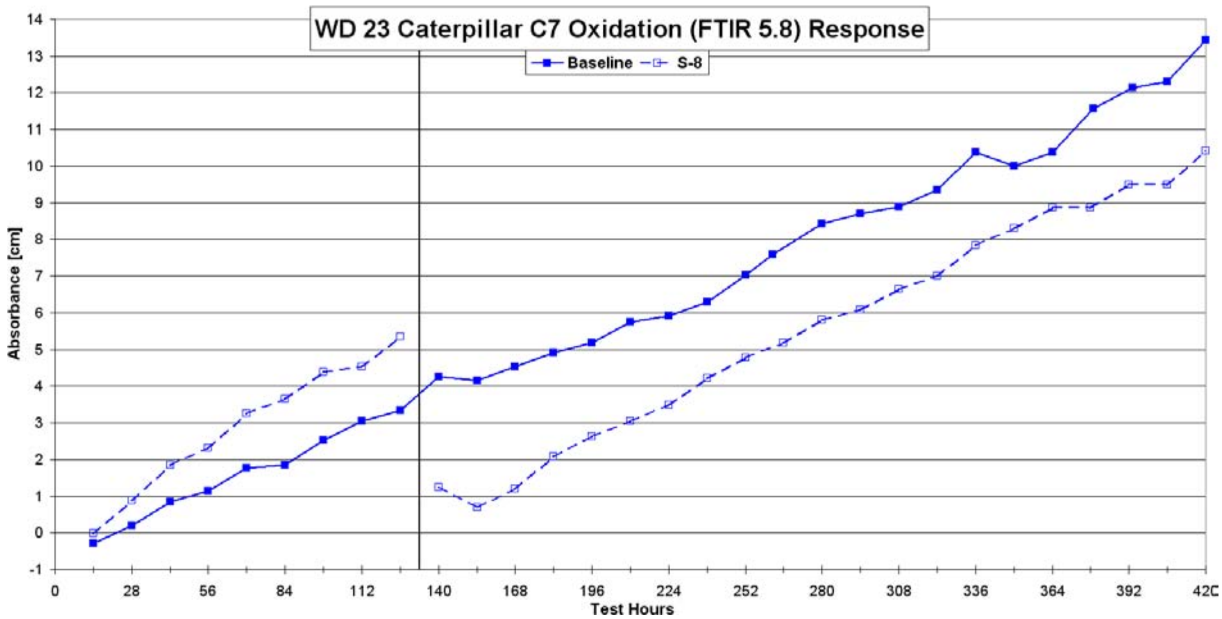


Figure 12. Oil Oxidation Test Results, Synthetic Fuel vs Baseline

- It is desirable for the result of this test not to exceed 30. No test results approached this limit.

- The plot from the S-8 test diverges above that for the Baseline test until the 132-hour oil loss. Having been displaced to lower numbers by the additions of new oil, it again trends upward, at a rate slightly greater than observed in the Baseline test. Overall, the very slight increase in oil oxidation during the S-8 test could be attributed to the slightly higher oil sump temperature of the S-8 test.

4.3.4 Soot

Figure 13 presents the overlaid results of soot content testing in each periodic sample of the tests previously described.

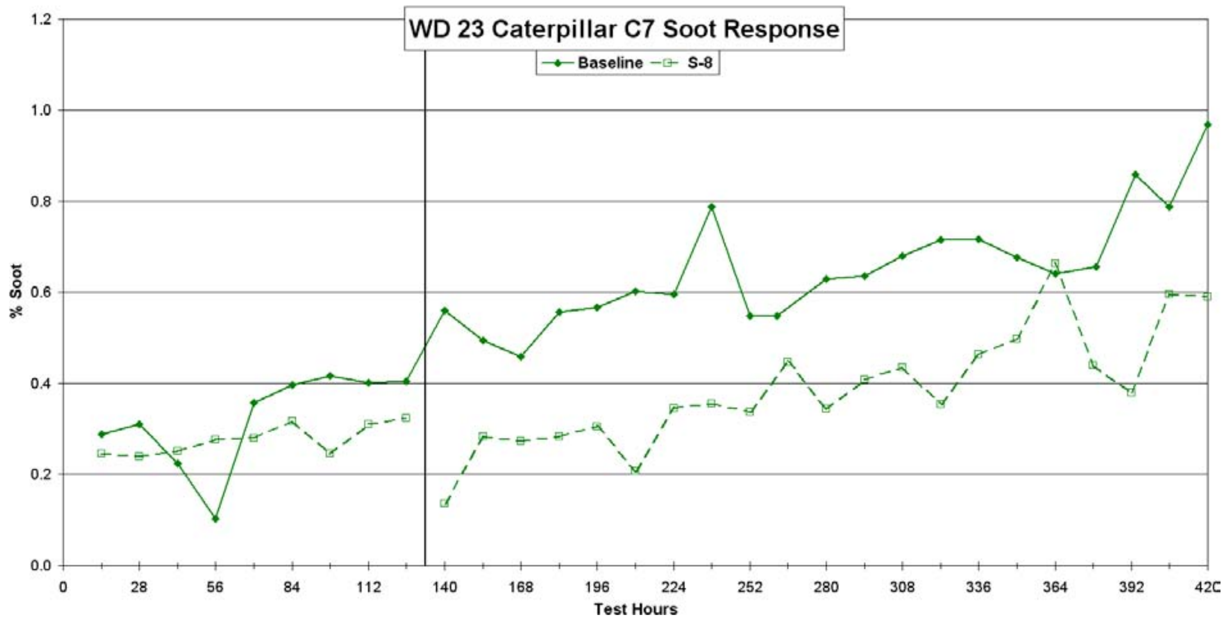


Figure 13. Oil Soot Content Test Results, Synthetic Fuel vs Baseline

- Some measurement inaccuracy is evinced in the oscillation of the plots, but follow discernable trends.

- It is desirable to change oil before soot reaches 3%. No soot measurement from either test exceeded 1%.

- The soot content of the oil was somewhat reduced when most of the dirty oil was replaced with clean oil after approximately 140 hours, however both plots follow approximately the same trend, indicating a similar soot contamination rate.

4.3.5 Viscosity

Figure 14 presents the overlaid results of oil viscosity measurements at 100° C, in each periodic sample of the tests previously described.

- In each test, the viscosity decreased by approximately 2 cSt during the first 14 hours of testing, apparently resulting from normal oil shear-down.

- The S-8 test results closely parallel those from the Baseline test.

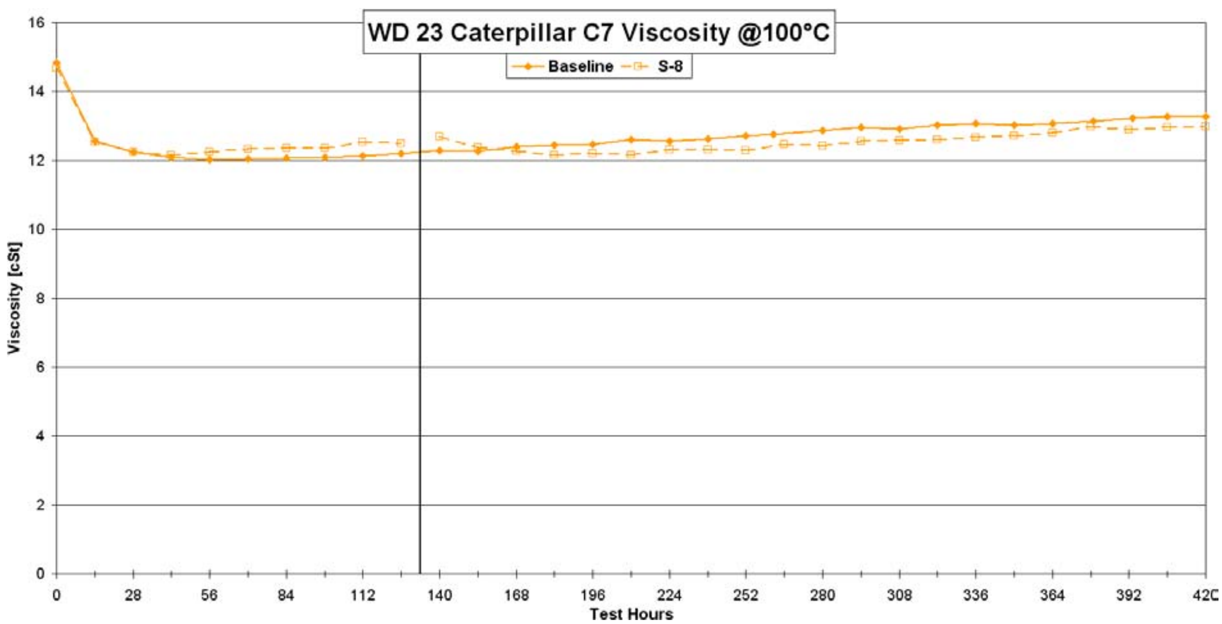
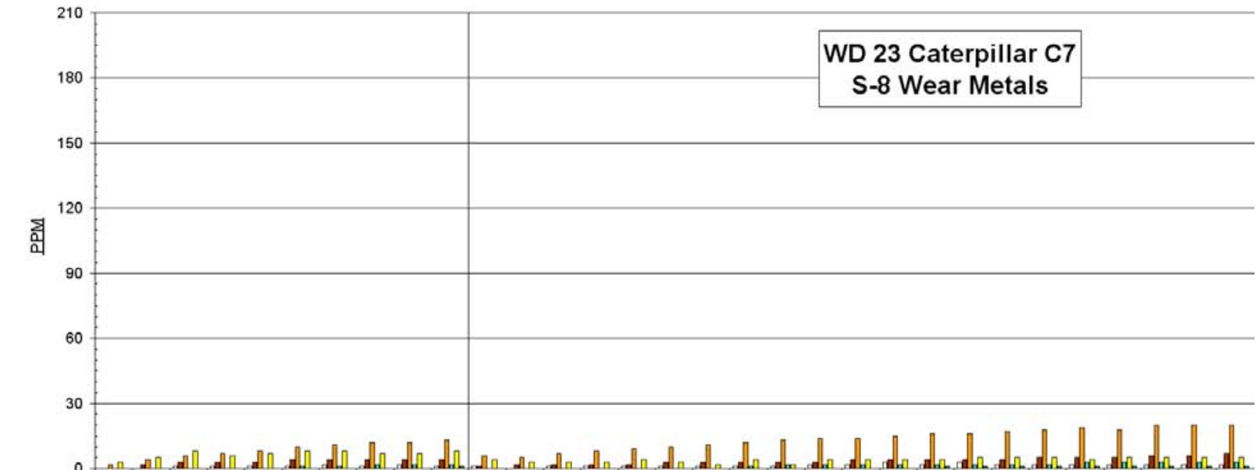


Figure 14. Oil 100°C Viscosity Test Results, Synthetic Fuel vs Baseline

4.4 Oil Wear Metals

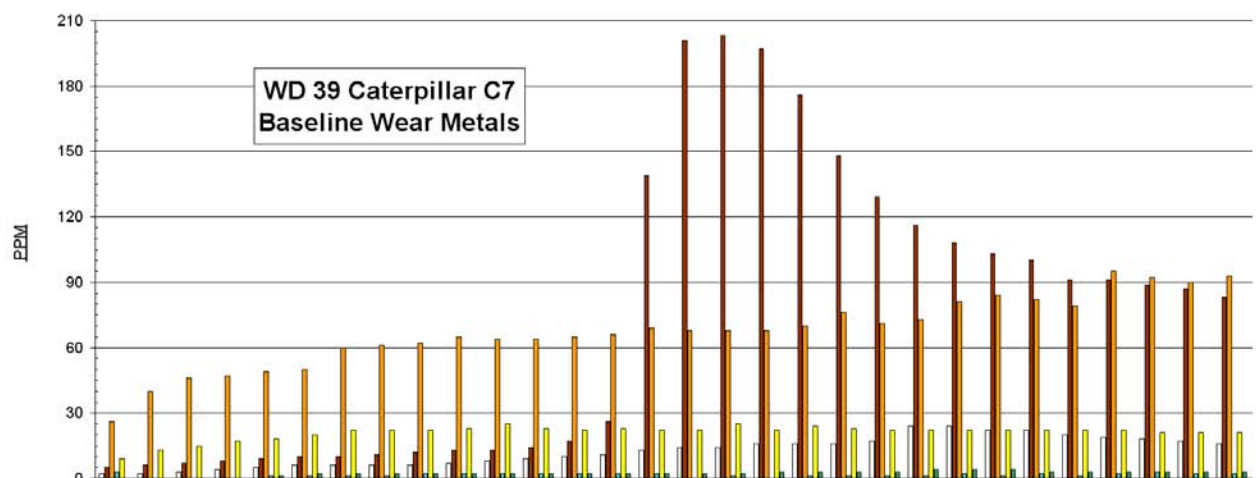
Figures 15 and 16 are graphs of the concentration of several engine wear metals in the lubricating oil for each test.

The sudden increase in copper particles in the oil for the baseline test at 210 hours in Figure 16 was likely caused by a main thrust bearing failure unrelated to lubrication. Even ignoring this effect, the difference between the wear metal concentrations is distinct, and may be attributable to engine to engine variation and manufacturing tolerances of the production test parts. The baseline and S-8 tests were conducted in different engine blocks.



Test Hours:	0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210	224	238	252	266	280	294	308	322	336	350	364	378	392	406	420
Aluminum	0	0	1	1	1	1	2	1	2	1	1	0	1	1	1	1	1	1	1	2	2	3	2	3	2	2	2	2	2	2	2
Copper	0	2	3	3	3	4	4	4	4	4	1	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	6	6	7
Iron	2	4	6	7	8	10	11	12	12	13	6	5	7	8	9	10	11	12	13	14	14	15	16	16	17	18	19	18	20	20	20
Lead	0	0	0	0	0	1	1	2	2	2	0	0	0	0	0	0	0	1	2	2	2	2	2	2	2	2	3	3	3	3	3
Silicon	3	5	8	6	7	8	8	7	7	8	4	3	3	3	4	3	2	4	2	4	4	4	4	5	5	5	4	5	5	5	5
Tin	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1

Figure 15. C7 Synthetic Fuel Test, Wear Metals



Test Hours	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210	224	238	252	262	280	294	308	322	336	350	364	379	393	406	420
Aluminum	2	2	3	4	5	6	6	6	6	7	8	9	10	11	13	14	14	16	16	16	17	24	24	22	22	20	19	18	17	16
Copper	5	6	7	8	9	10	10	11	12	13	13	14	17	26	139	201	203	197	176	148	129	116	108	103	100	91	91	89	87	83
Iron	26	40	46	47	49	50	60	61	62	65	64	64	65	66	69	68	68	68	70	76	71	73	81	84	82	79	95	92	90	93
Lead	3	0	0	0	1	1	1	1	2	2	2	2	2	2	2	0	1	0	1	1	1	1	2	1	2	1	2	3	2	2
Silicon	9	13	15	17	18	20	22	22	22	23	25	23	22	23	22	22	25	22	24	23	22	22	22	22	22	22	22	21	21	21
Tin	0	0	0	0	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	4	4	4	3	3	3	3	3	3

Figure 16. C7 Baseline Test, Wear Metals

4.5 Engine Deposits and Wear Evaluation

As noted in section 2, the critical components of each engine are evaluated after testing to identify and quantify wear and deposits. Those evaluations are extensively documented in the attached individual test reports. Table 4, below, presents a comparative synopsis of some parameters.

Table 4. Comparison of Post-Test Wear and Deposit Evaluations

Test Description		**Baseline**	**S-8**
Parameter			
Ring Sticking		1	0
Average Top Groove Carbon Fill	[%]	38.3	20.2
Average Top Land Heavy Carbon	[%]	16.5	2.2
Average Piston Deposits	[demerits]	127.8	123.3
Scuffing, average area	[%]		
Rings, Piston Crown & Skirt		6.7	0.0
Cylinder		10.8	0.0
Valve Tulip Deposit	[average merits]		
Exhaust Valves		8.0	8.0
Intake Valves		8.8	8.0
Average Cylinder Bore Change	[in/1000]	+ 0.3	-0.6
Average Top Ring Radial Wear	[in/1000]	0.00	0.16
Average Piston Ring Gap Change	[in/1000]		
Ring 1		- 0.7	- 2.5
Ring 2		- 1.2	- 2.3
Ring 3		- 2.3	- 2.8
Average Piston Ring Mass Loss	[mg]		
Ring 1		23.3	8.0
Ring 2		4.1	3.0
Ring 3		9.5	8.3
Average Bearing Mass Loss	[mg]		
Main Bearing		288.8	18.7
Connecting Rod Bearing		11.9	26.6

Wear in the Baseline engine included scuffing in two cylinders and damage to the thrust face of the main bearing. These are reflected in the main bearing mass loss being an order of magnitude greater in that engine, as well as the scuffing ratings and the top piston ring mass loss. These events somewhat cloud the comparison, but even in unaffected areas, the Synthetic Fuel test returned better results. Even with the increased oil consumption previously noted, overall average piston deposits (demerits) are comparable to the Baseline test.

5.0 CONCLUSIONS

Despite the elevated air, coolant and oil temperatures, the engine completed the 420-hour test cycle, designed to simulate 40,000 miles of proving ground operation, without sufficient degradation of any oil property to cease the test. The component failures that did occur during testing were not apparently fuel- or lubricant-related. While the engine did exhibit increased oil consumption, it is likely not related to the synthetic fuel.

Performance and emissions measurements performed with the engine prior to endurance testing demonstrated little difference among the S-8, JP-8 and S-8/JP-8 blend fuels. The DF-2 fuel produced markedly greater CO, less HC, and more power than any of the other fuels.

Most chemical analyses of the engine lubricating oil showed little difference between the Synthetic Fuel test and the Baseline test, with the exception that the oil apparently oxidized slightly more rapidly during the S-8 test. This is probably due to the slightly higher oil sump temperature during the S-8 test. There was a much greater difference between the tests in terms of wear metal concentration in the oil: there was distinctly less wear metal found with the synthetic fuel, obvious even in the presence of confounding factors. These differences are probably more related to engine and production part variations than the type of fuel used.

There was no significant wear or deposits in the engine post-test. One injector did fail at idle conditions during the endurance testing, but not apparently due to deposits or any other effect of the synthetic fuel.

6.0 REFERENCES

1. Coordinating Research Council, Inc., "Development of Military Fuel/Lubricant/Engine Compatibility Test," CRC Report No. 406, January 1967.

2. Schulman, Matthew E. and Frame, Edwin A., "Evaluation of Oil Management Systems (OMS) Using Caterpillar C7 Engine," TFLRF Interim Report No. 388, ADB326177, April 2007.

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APPENDICES

Individual Test Reports

Appendix A

Electronic Data Acquired

Time Of Day	s
Time Under Test	s
Engine Power	bhp
Engine Speed	rpm
Engine Torque	lb-ft
Brake Specific Fuel Consumption	lbm/HP·hr
Air Temperature Before Compressor	°F
Air Temperature After Compressor	°F
Intake Manifold Air Temperature	°F
Exhaust Cylinder 1 Temperature	°F
Exhaust Cylinder 2 Temperature	°F
Exhaust Cylinder 3 Temperature	°F
Exhaust Cylinder 4 Temperature	°F
Exhaust Cylinder 5 Temperature	°F
Exhaust Cylinder 6 Temperature	°F
Exhaust Front Manifold Temperature	°F
Exhaust Rear Manifold Temperature	°F
Exhaust Stack Temperature	°F
Coolant from Engine Temperature	°F
Coolant to Engine Temperature	°F
Fuel Inlet Temperature	°F
Oil Gallery Temperature	°F
Oil Sump Temperature	°F
Ambient Pressure	psiA
Intake Before Compressor Pressure	psiA
Intake After Compressor Pressure	psiA
Boost Pressure	psiA
Exhaust After Turbine Pressure	psiG
Exhaust Before Turbine Pressure	psiG
Coolant Pressure	psiG
Fuel Pressure	psiG
Oil Gallery Pressure	psiG
Blowby Gas Flow Rate	acfm
Fuel Mass Flow Rate	lbs/hr

Appendix B

Product: SAE Grade 15W40 **Source Tank:** 35 **Manufacturer:** Imperial Oil Co., Inc.

Specification: MIL – PRF – 2104G **Batch:** 940 **Manufacturer Location:** Morganville, New Jersey

Qualification: PRI EO 0022 **Certification:** 1140 **Date:** October 06, 2005

Amount Sample Represents: 16,000 gals. AL-27170-[illegible]L

	Spec./ Qual.	Results		Spec./ Qual. Tend.	Spec./ Qual. Stab.	Results Tend.	Results Stab.
Gravity API°	26.9 – 28.9	28.2	Foam:				
Flash Point °C	215 min.	230° C	Sequence 1	10 max.	0	0	0
Viscosity @ 100°C cSt.	14.58 – 15.58	14.83	Sequence 2	20 max.	0	10	0
Viscosity @ 40°C cSt.	99.02 – 129.02	116.69	Sequence 3	10 max.	0	0	0
Viscosity Index	Report	137	Sequence 4	50 max.	0	10	0
Vis. Cp @ - 15°C CCS.	3500 max.	3240	Total Base Number	Report		8.129	
Vis. Cp @ - 20°C CCS.	3500 min.	5970	Total Acid Number	Report		1.91	
Pumpability, Vis., CP@ - 25°C	Report	< 30,000	Phosphorous Wt. %	0.1053 – 0.1404		0.1247	
Hi Temp., Hi Shear, Vis. CP	3.7 min.	4.29	Magnesium Wt. %	0.00 - < 0.01		0.0039	
Ramsbottom Carbon Wt. %	0.97 - 1.27	1.015	Silicone Wt. %	0.00 - < 0.01		0.0034	
Sulfated Ash Wt. %	1.143 – 1.524	1.212	Chlorine Wt. %	0.01 - < 0.03		0.0179	
Sulfur Wt. %	0.56 – 0.84	0.693	Nitrogen Wt. %	0.0685 min.		0.0817	
Sulfur (additive) Wt. %	0.387 – 0.516	0.454	Boron Wt. %	0.00 - < 0.01		0.00	
Calcium Wt. %	0.2619 – 0.3492	0.2844	Copper Wt. %	0.00 - < 0.01		0.00	
Zinc Wt. %	0.1161 – 0.1548	0.1303	Potassium Wt. %	0.00 - < 0.01		0.00	
Pour Point °C	- 23 max.	< - 23° C	Barium Wt. %	0.00 - < 0.01		0.00	
Stable Pour Point °C	- 23 max.	< - 23° C	Sodium Wt. %	0.00 - < 0.01		0.00	

Laboratory Supervisor: Antonio O. Enriquez

Government Inspector: **Date:** October 06, 2005

Product Meets Specifications For Tests Performed.

Appendix C

The Fischer-Tropsch fuel used for this test was a blend of two batches and designated AL-27755. The total 7000 gallons was prepared using 2000 gallons from ISO container 124146-1 and 5000 gallons from ISO container 124248-9. Certificates of Analysis for each of these constituents are attached.

Certificate of Analysis – Isoparaffinic Synthetic Distillate

Syntroleum®

THIS SYNTROLEUM FISCHER-TROPSCH SYNTHETIC RESEARCH FLUID HAS BEEN PRODUCED FOR THE DEPARTMENT OF DEFENSE PURSUANT TO A FIXED FEE PLUS COST-REIMBURSEMENT U.S. GOVERNMENT CONTRACT, NUMBER F33615-02-D-2299

ISO CONTAINER NUMBER:124146-1B

DATE OF TESTING: 19-Jul-06

PROPERTY	TEST METHOD	UNITS	SPECIFICATION		ACTUAL
			MINIMUM	MAXIMUM	
Density @ 15 °C	ASTM D-4052	kg/L	0.75	0.77	0.755
API @ 60 °F	ASTM D-4052		51.6	56.5	55.9
Ash, max	ASTM D-482	wt%		0.001	<0.001
Flash Point	ASTM D-93	°C	38		47.0
Freezing Point	ASTM D-5972	°C		-47	-50.5
Color	ASTM D-156	Saybolt		Report	+28
Viscosity	ASTM D-445	cSt @ 40°C	1.3	1.9	1.328
Distillation, IBP,%	ASTM D-2887	°C		Report	114
10% recovered		°C		186	151
20% recovered		°C		Report	169
50% recovered		°C		Report	209
90% recovered		°C		Report	259
FBP		°C		330	280
Conductivity @ 85 °F	ASTM D-2624	pS/m	150	450	356
Cetane Index (calculated)	ASTM D-976			Report	68.2
Antioxidant (2,6-di-tert-butylphenol)		mg/L	17.2	24.0	21
Corrosion Inhibitor / Lubricity Improver (supplied by AF)		g/m^3	13	17	15

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4322 SOUTH 49TH WEST AVENUE
TULSA, OKLAHOMA 74107
(918) 592-7900

SYNTROLEUM QA/QC APPROVAL

Christine A. King
Authorized Signature

JULY 21, 2006
Date

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Certificate of Analysis – Isoparaffinic Synthetic Distillate

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ISO CONTAINER NUMBER: 124248-9

DATE OF TESTING: 17-Jul-06

PROPERTY	TEST METHOD	UNITS	SPECIFICATION		ACTUAL
			MINIMUM	MAXIMUM	
Density @ 15 °C	ASTM D-4052	kg/L	0.75	0.77	0.755
API @ 60 °F	ASTM D-4052		51.6	56.5	55.6
Ash, max	ASTM D-482	wt%		0.001	<0.001
Flash Point	ASTM D-93	°C	38		48.0
Freezing Point	ASTM D-5972	°C		-47	-50.0
Color	ASTM D-156	Saybolt		Report	+28
Viscosity	ASTM D-445	cSt @ 40°C	1.3	1.9	1.326
Distillation, IBP,%	ASTM D-2887	°C		Report	114
10% recovered		°C		186	151
20% recovered		°C		Report	172
50% recovered		°C		Report	210
90% recovered		°C		Report	260
FBP		°C		330	280
Conductivity @ 85 °F	ASTM D-2624	pS/m	150	450	233
Cetane Index (calculated)	ASTM D-976			Report	67.9
Antioxidant (2,6-di-tert-butylphenol)		mg/L	17.2	24.0	21
Corrosion Inhibitor / Lubricity Improver (supplied by AF)		g/m^3	13	17	15

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TULSA, OKLAHOMA 74107
(918) 592-7900

SYNTROLEUM QA/QC APPROVAL

Christine A. King — **17-JUL-06**

Authorized Signature — Date

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Appendix D

AGE REFINING, INC.

REFINING OFFICE:
7811 S. Presa
San Antonio, Texas 7822:
(210) 532-5300
(210) 532-7222 Fax

Product Name: JP-8

Tank: 424
Batch: 424DH
Date: 06/15/06

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
Color, Saybolt	D 156		Report	+28
Total Acid, mg KOH/g	D 3242		0.015	0.006
Aromatics, vol%	D 1319		25	17.8
Olefins, vol%	D 1319		5.0	0.6
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.012
Distillation temperature, ^{o}C	D 86			
•IBP			Report	145
•10% recovered, temp			205	158
•20% recovered, temp			Report	164
•50% recovered, temp			Report	182
•90% recovered, temp			Report	230
•End Point, temp			300	251
•Residue, vol%			1.5	0.9
•Loss, vol%			1.5	0.0
Flash Point, ^{o}F	D 93	100		104
Gravity, API, at 15^{o}C	D 1298	51.0	37.0	47.9
Freeze Point, ^{o}C	D 2386		-47	-52.50
Viscosity @ -20^{o}C	D 445		8.0	3.07
Heat of combustion, BTU/lb	D 3338	18,400		18,631
Hydrogen content, mass%	D 3701	13.4		13.93
Smoke Point, mm	D 1322	19		26.0
Copper corrosion, 2 hr @ 100^{o}C	D 130		1	1A
Thermal Stability	D 3241			
• Pressure drop, mm Hg			25	0.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	1.2
Particulate matter, mg/L	D 5452		1	0.61
Filtration time, minutes	D 5452		15	5
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		95
Additives **(Corrosion Inhibitor and Static Dissipator)**				
Moisture, mg/Kg	D 6304		Report	56
Fuel System Icing Inhibitor	D 5006	0.10	0.15	0.110
Calculated Cetane Index	D 976		Report	41.1

Report Date: ______________

Analysis performed by: ____________________

Appendix E

EVALUATION OF OIL MANAGEMENT SYSTEMS (OMS)

WORK DIRECTIVE NO. 39

Caterpillar C7

OMS Equipment: ASTI Oil Sensor
Test Lubricant: AL-27170-L
Army Reference Oil, MIL-PRF-2104G, SAE 15W40
Test Fuel: JP8
Test Number :FMM03101-1A
Start of Test Date: 1 June 2006
End of Test Date: 29 June 2006
Test Duration: 420 Hours
Test Procedure: Extended Tactical Wheeled Vehicle

Conducted For

U.S. Army RDECOM
Tank-Automotive Research, Development & Engineering Center
Petroleum and Water Business Area
Warren, Michigan 48397-5000

By

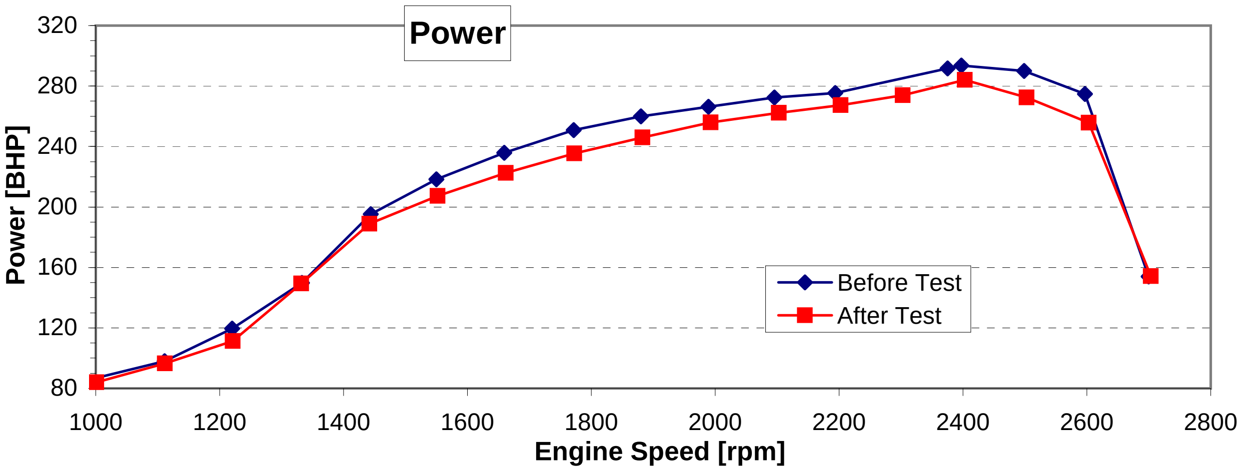
TARDEC Fuel and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

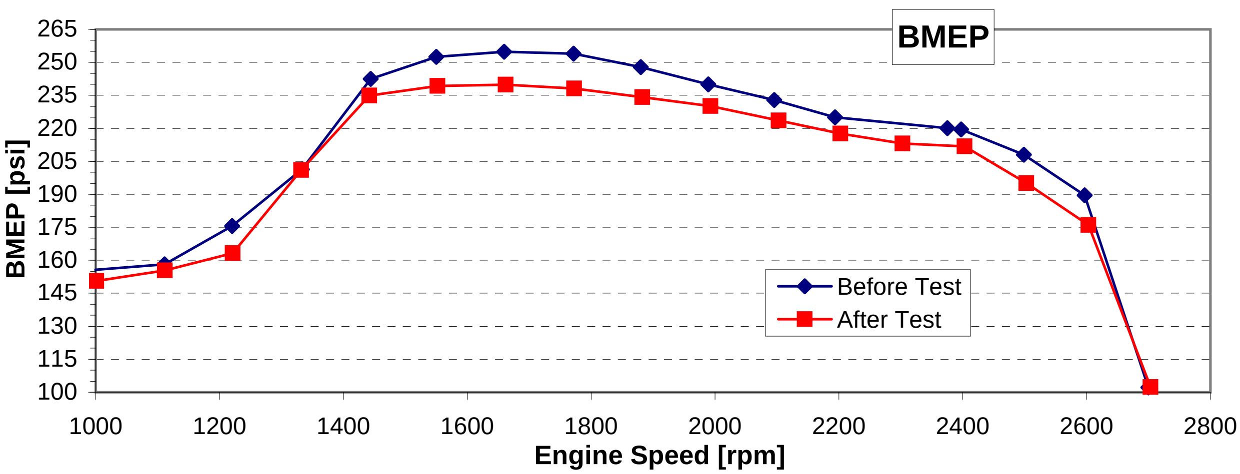
Contract DAAE07-99-C-L053

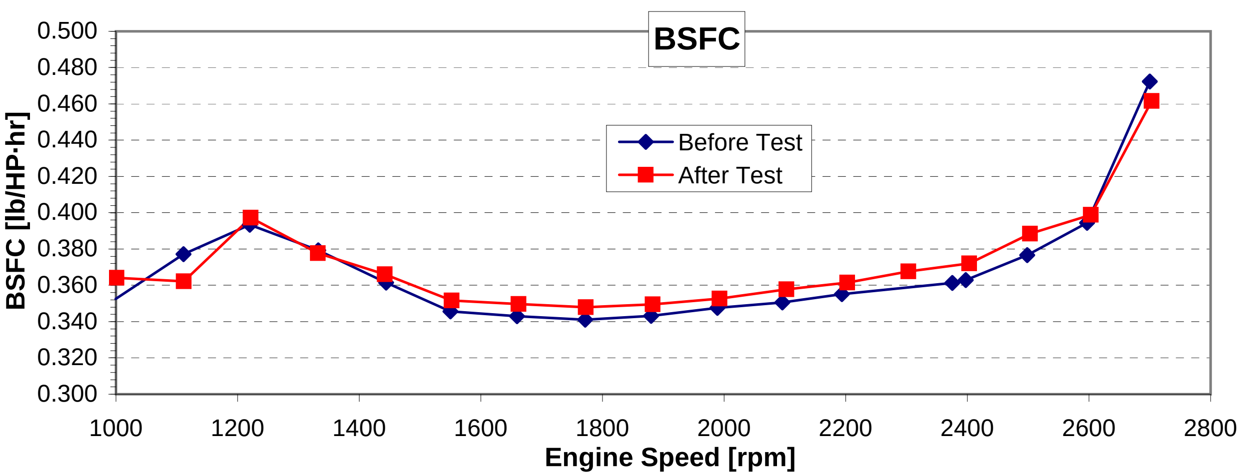
Engine Operating Conditions Summary

	Maximum Power Mode (2400 rpm)		Idle Mode (700 rpm) (first 128 test hours)		Idle Mode (750 rpm) (remainder of test)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Performance						
Engine Speed [rpm]	2402.0	20.1	700.0	1.3	749.9	1.2
Torque [ft·lb]	657.2	76.4	10.6	3.3	9.5	5.4
Fuel Consumption [lb/hr]	107.7	3.5	3.0	0.1	3.3	0.1
Observed Power [Bhp]	300.5	34.8	1.4	0.4	1.3	0.8
BSFC [lb/Bhp·hr]	0.360	0.016	2.30	0.60	3.50	1.98
Temperatures [°F]						
Oil Sump	258.2	1.4	132.7	6.4	132.6	7.5
Water Jacket Inlet	209.2	4.2	107.1	5.1	107.4	7.9
Water Jacket Outlet	217.5	3.2	110.3	5.4	110.6	7.7
Fuel Inlet to Pump	117.7	2.9	96.1	5.6	98.3	5.2
Fuel Return	172.1	2.3	112.0	6.0	111.7	6.6
Inlet Air	104.4	10.3	89.9	6.5	90.5	4.9
Intake Manifold Air	140.5	9.9	79.2	1.2	79.7	1.3
Exhaust Port Cylinder 1	927.9	23.2	180.2	6.0	200.1	12.2
Exhaust Port Cylinder 2	1084.3	21.7	186.4	6.7	198.0	10.2
Exhaust Port Cylinder 3	1104.1	21.5	191.9	6.1	202.6	12.7
Exhaust Port Cylinder 4	1088.4	22.3	204.6	7.2	199.9	23.8
Exhaust Port Cylinder 5	1115.6	32.3	195.7	7.3	212.7	8.8
Exhaust Port Cylinder 6	1031.0	96.5	212.7	6.3	223.9	23.0
Exhaust, Front Before Turbo	1083.8	131.7	195.6	3.4	208.8	12.6
Exhaust, Rear Before Turbo	1145.0	34.1	210.2	4.2	215.1	9.0
Exhaust After Turbo	881.2	25.6	190.8	4.6	198.6	3.4
Pressures						
Oil [psi]	45.3	1.7	57.3	2.3	56.7	2.6
Barometer [psiA]	14.2	0.1	14.2	0.1	14.2	0.1
Intake Before Compressor [psiA]	13.8	0.1	14.3	0.0	14.3	0.1
Intake After Compressor [psiA]	42.8	0.2	14.4	0.1	14.5	0.1
Exhaust Before Turbo [psig]	27.3	0.8	0.1	0.1	0.0	0.1
Exhaust After Turbo [psig]	1.2	0.2	-0.3	0.0	-0.3	0.1
Emissions						
CO [ppm]	536	32.2	---	---	---	---
CO_2 [%]	7.69	0.16	---	---	---	---
HC [ppm]	11	23.0	---	---	---	---
NO_X [ppm]	430	25.8	---	---	---	---
O_2 [%]	10.28	0.22	---	---	---	---
Smoke [% opacity]	0.6	0.5	---	---	---	---

Engine Performance Curves







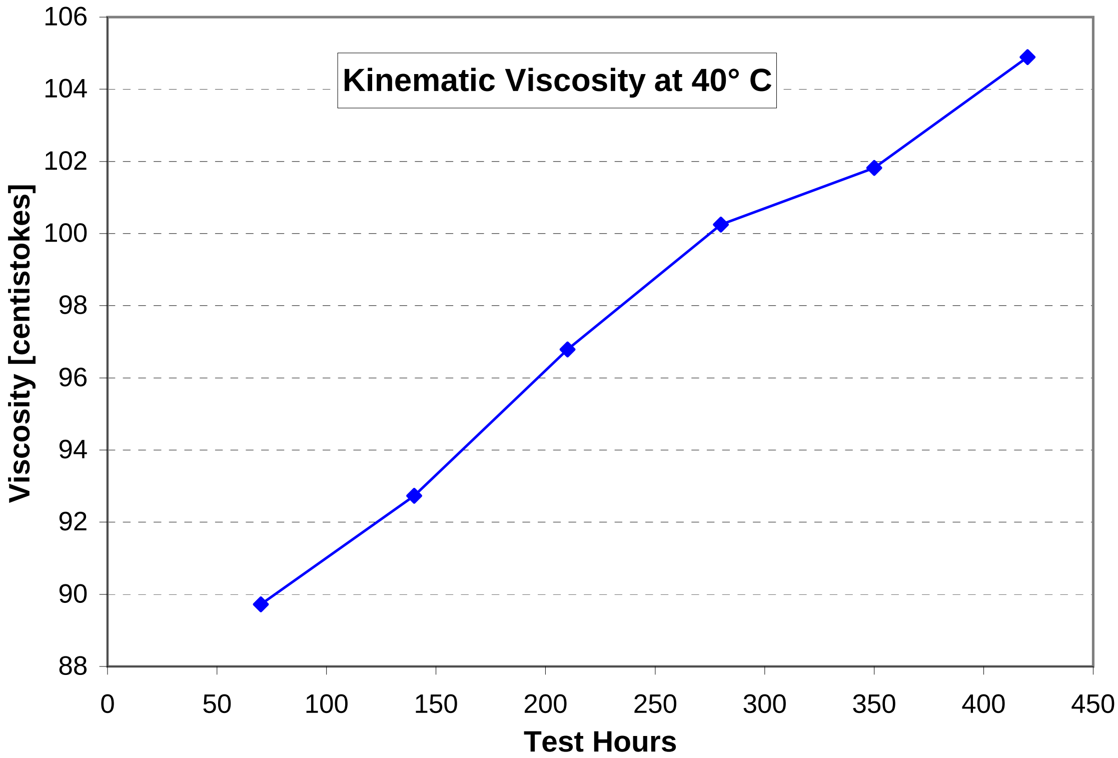
Emissions Data

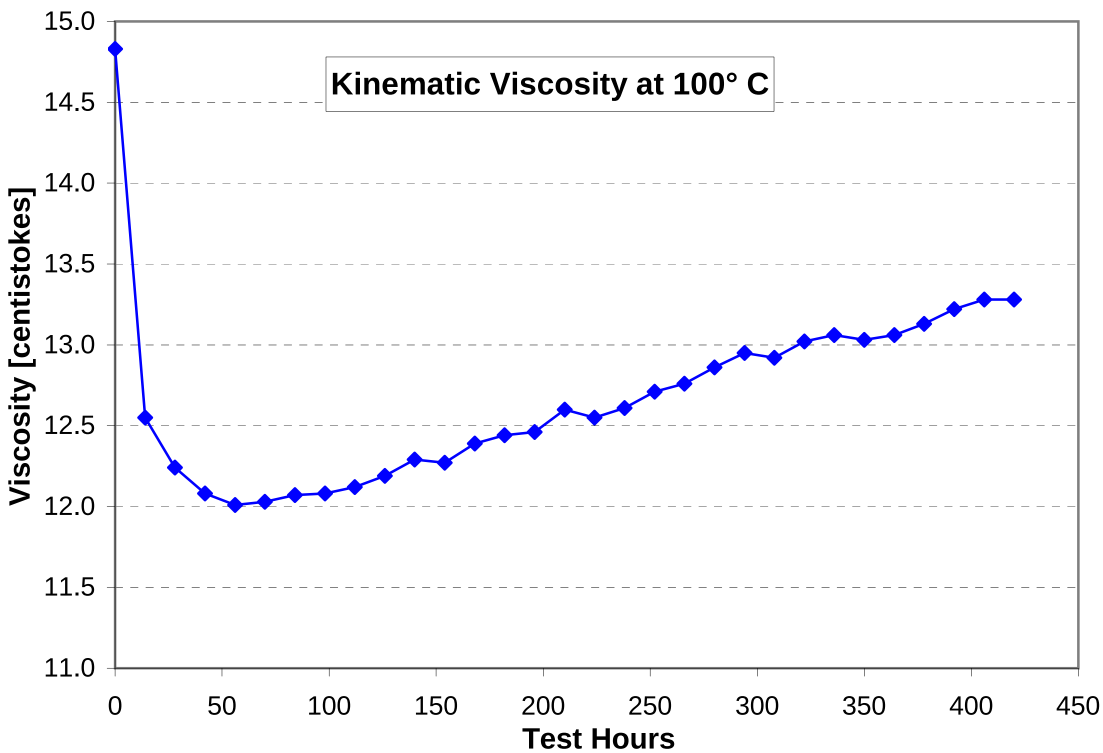
Test Hours	Smoke [% opacity]	NO_X [ppm]	O_2 [%]	CO_2 [%]	CO [ppm]	HC [ppm]
1	0.7	485	10.42	7.59	537	0
21	0.7	432	10.24	7.72	556	60
41	0.4	463	10.58	7.47	501	10
61	0.5	439	10.47	7.55	497	30
81	1.4	423	10.25	7.71	510	70
101	0.7	459	10.24	7.71	505	60
121	0.9	434	9.87	7.98	535	0
141	0.6	414	9.99	7.90	537	0
161	0.5	416	10.09	7.82	530	0
181	0.8	427	10.20	7.74	549	0
201	1.2	475	10.36	7.63	589	0
221	2.1	384	10.18	7.76	604	0
241	0.3	408	10.19	7.75	605	0
261	0.5	448	9.90	7.96	504	0
281	0.5	426	10.19	7.75	517	0
301	0.4	412	10.21	7.73	544	0
321	0.2	430	10.43	7.58	520	0
341	0.1	421	10.38	7.62	520	0
361	0.2	411	10.31	7.67	536	0
381	0.1	435	10.66	7.41	502	0
401	0.1	385	10.64	7.43	557	0
Minimum	0.1	384	9.87	7.41	497	0
Maximum	2.1	485	10.66	7.98	605	70
Average	0.6	430	10.28	7.69	536	11.0
Standard Deviation	0.48	25.8	0.216	0.155	32.2	23.0

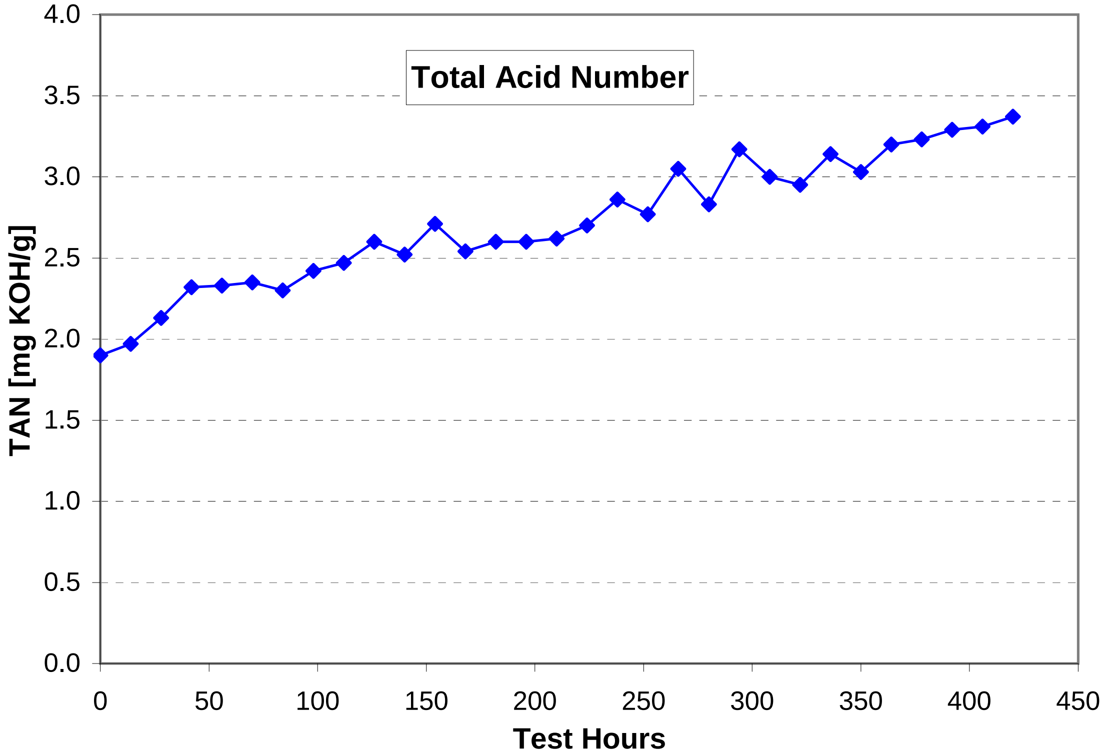
Lubricant Analysis

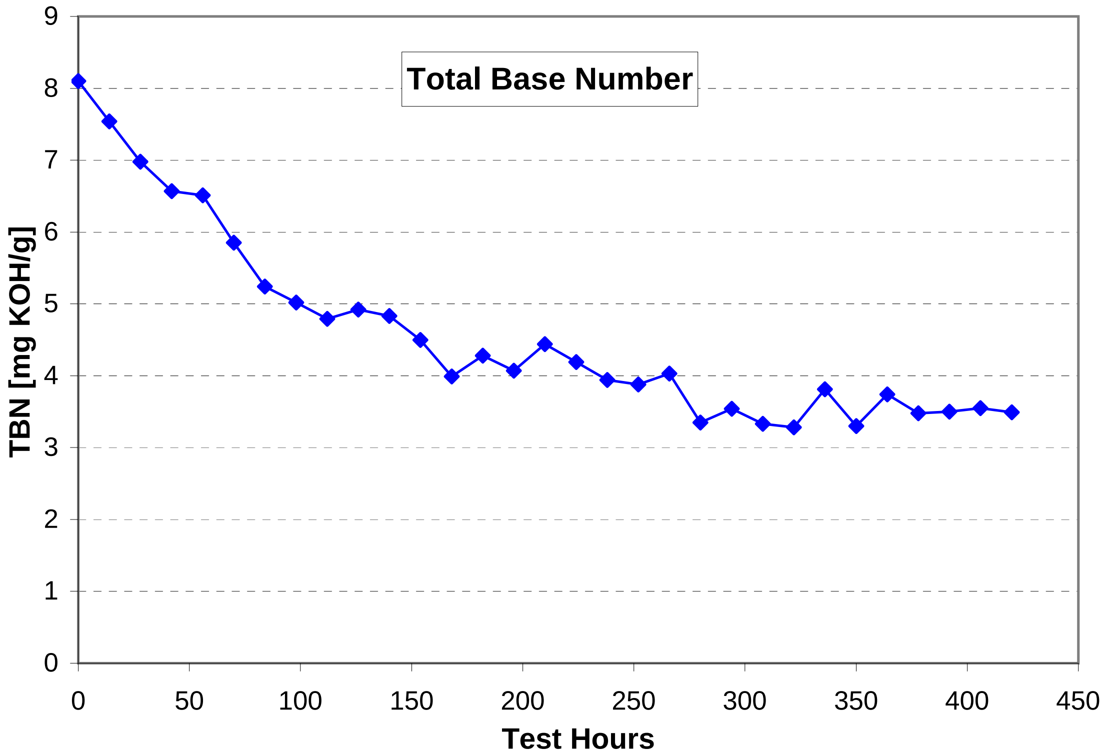
Test Hours	0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210
Total Base Number [mg KOH/g] (ASTM D 4739)	8.10	7.54	6.98	6.57	6.51	5.85	5.24	5.02	4.79	4.92	4.83	4.50	3.99	4.28	4.07	4.44
Total Acid Number [mg KOH/g] (ASTM D 664)	1.90	1.97	2.13	2.32	2.33	2.35	2.30	2.42	2.47	2.60	2.52	2.71	2.54	2.60	2.60	2.62
Kinematic Viscosity at 100°C [cSt] (ASTM D 445)	14.83	12.55	12.24	12.08	12.01	12.03	12.07	12.08	12.12	12.19	12.29	12.27	12.39	12.44	12.46	12.60
Kinematic Viscosity at 40°C [cSt] (ASTM D 445)		---	---	---	---	89.72	---	---	---	---	92.73	---	---	---	---	96.79
Viscosity Index (ASTM D 2270)		---	---	---	---	127	---	---	---	---	126	---	---	---	---	125
API Gravity (ASTM D 4052)		27.9	27.8	27.8	28.3	27.6	28.2	27.6	27.5	27.6	27.3	27.8	27.6	27.6	27.5	27.5
Density (ASTM D 4052)		0.8867	0.8872	0.8876	0.8845	0.8885	0.8854	0.8886	0.8893	0.8887	0.89	0.8885	0.8895	0.8893	0.8896	0.8898
Soot (TGA)		0.289	0.310	0.224	0.103	0.358	0.396	0.417	0.402	0.405	0.560	0.495	0.459	0.557	0.567	0.602
Oxidation [Abs./cm] (ASTM E 168)		-0.29	0.19	0.85	1.14	1.76	1.85	2.53	3.04	3.33	4.26	4.16	4.53	4.9	5.18	5.74
Nitration [Abs./cm] (ASTM E 168)		0.09	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.09	0.19	0.09	0.09	0	0	0
Wear Metals by ICP, ppm (ASTM D 5185)																
Iron		26	40	46	47	49	50	60	61	62	65	64	64	65	66	69
Copper		5	6	7	8	9	10	10	11	12	13	13	14	17	26	139
Aluminum		2	2	3	4	5	6	6	6	6	7	8	9	10	11	13
Silicon		9	13	15	17	18	20	22	22	22	23	25	23	22	23	22
Silver		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tin		-	-	-	-	1	2	2	2	2	2	2	2	2	2	2
Lead		3	-	-	-	1	1	1	1	2	2	2	2	2	2	2

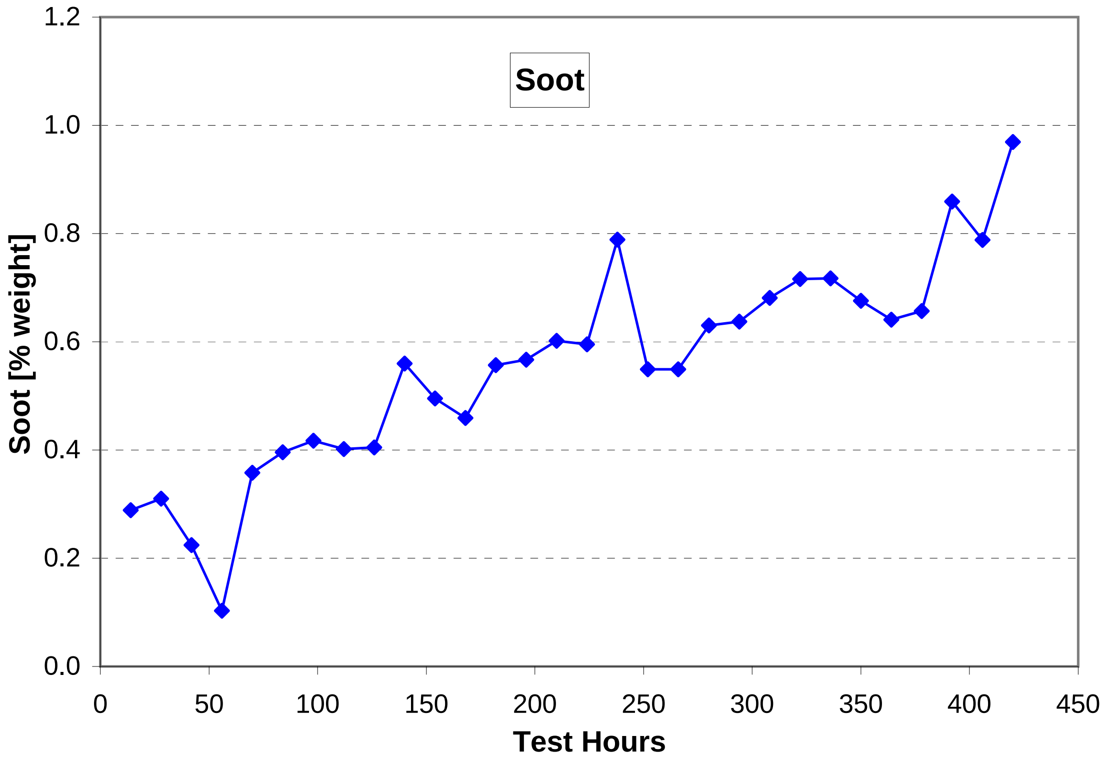
Test Hours	224	238	252	266	280	294	308	322	336	350	364	378	392	406	420
Total Base Number [mg KOH/g] (ASTM D 664)	4.19	3.94	3.88	4.03	3.35	3.54	3.33	3.28	3.81	3.30	3.74	3.48	3.50	3.55	3.49
Total Acid Number [mg KOH/g] (ASTM D 4739)	2.70	2.86	2.77	3.05	2.83	3.17	3.00	2.95	3.14	3.03	3.20	3.23	3.29	3.31	3.37
Kinematic Viscosity at 100°C [cSt] (ASTM D 445)	12.55	12.61	12.71	12.76	12.86	12.95	12.92	13.02	13.06	13.03	13.06	13.13	13.22	13.28	13.28
Kinematic Viscosity at 40°C [cSt] (ASTM D 445)	---	---	---	---	100.25	---	---	---	---	101.82	---	---	---	---	104.89
Viscosity Index (ASTM D 2270)	---	---	---	---	124	---	---	---	---	125	---	---	---	---	124
API Gravity (ASTM D 4052)	29.2	27	27	26.9	26.8	26.8	26.8	26.8	26.7	23.5	26.7	26.6	26.6	26.6	26.5
Density (ASTM D 4052)	0.8904	0.8917	0.8918	0.8924	0.8929	0.8931	0.8931	0.8932	0.8936	0.9118	0.8937	0.8942	0.8944	0.8945	0.8951
Soot (TGA)	0.595	0.789	0.549	0.549	0.630	0.637	0.681	0.716	0.717	0.676	0.641	0.657	0.859	0.788	0.969
Oxidation [Abs./cm] (ASTM E 168)	5.92	6.29	7.03	7.59	8.42	8.7	8.89	9.35	10.37	10	10.37	11.57	12.13	12.31	13.43
Nitration [Abs./cm] (ASTM E 168)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28
Wear Metals by ICP, ppm (ASTM D 5185)															
Iron	68	68	68	70	76	71	73	81	84	82	79	95	92	90	93
Copper	201	203	197	176	148	129	116	108	103	100	91	91	89	87	83
Aluminum	14	14	16	16	16	17	24	24	22	22	20	19	18	17	16
Silicon	22	25	22	24	23	22	22	22	22	22	22	22	21	21	21
Silver	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-
Tin	2	2	3	3	3	3	4	4	4	3	3	3	3	3	3
Lead	-	1	-	1	1	1	1	2	1	2	1	2	3	2	2

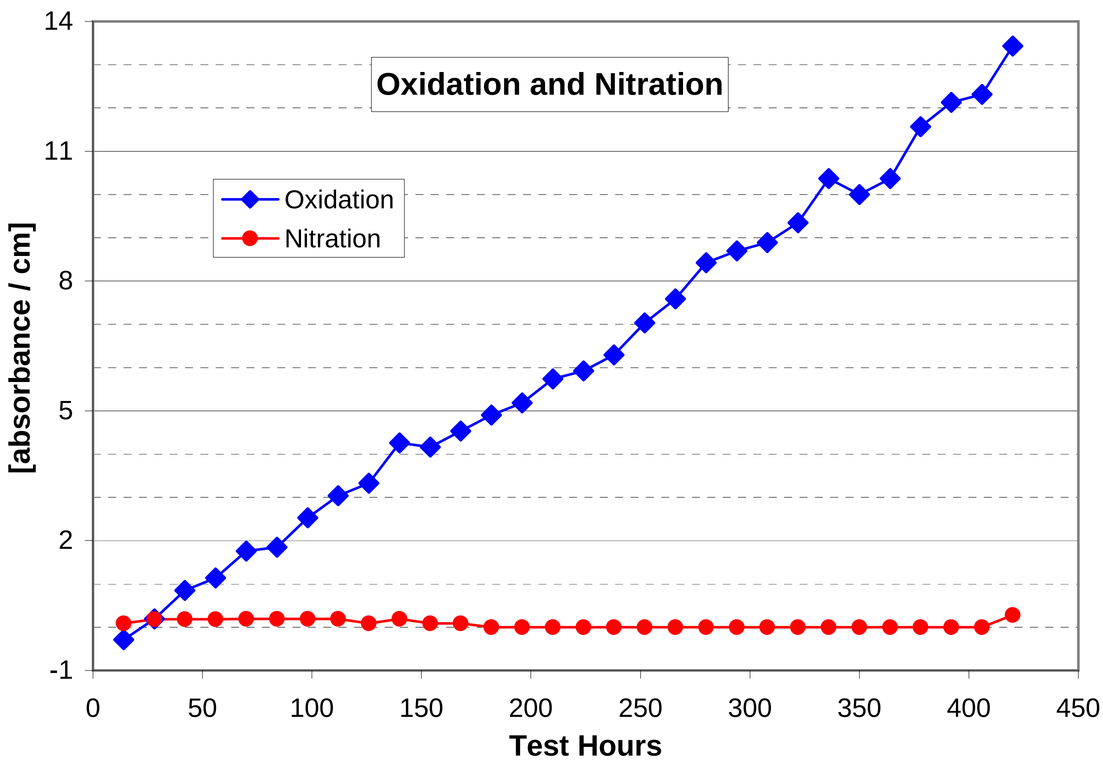

Kinematic Viscosity at 40° C
Viscosity [centistokes]
Test Hours
106
104
102
100
98
96
94
92
90
88
0
50
100
150
200
250
300
350
400
450

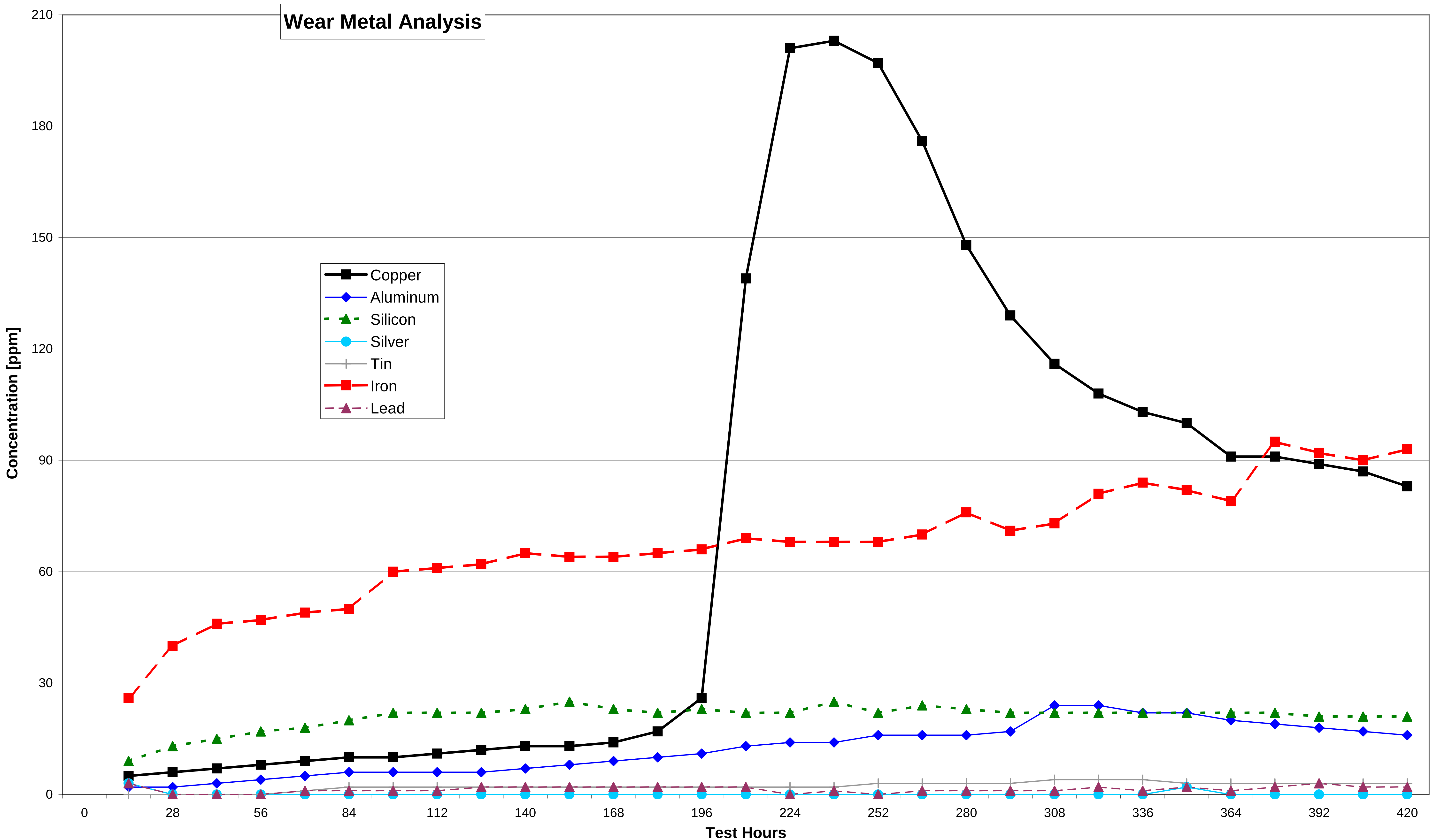

Kinematic Viscosity at 100° C
Viscosity [centistokes]
Test Hours
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
0
50
100
150
200
250
300
350
400
450


Total Acid Number
TAN [mg KOH/g]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
450
Test Hours


Total Base Number
TBN [mg KOH/g]
9
8
7
6
5
4
3
2
1
0
0
50
100
150
200
250
300
350
400
450
Test Hours


Soot
Soot [% weight]
Test Hours
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200
250
300
350
400
450


Oxidation and Nitration
Oxidation
Nitration
[absorbance / cm]
Test Hours
-1
2
5
8
11
14
0
50
100
150
200
250
300
350
400
450


Wear Metal Analysis
Concentration [ppm]
Test Hours
0
30
60
90
120
150
180
210
0
28
56
84
112
140
168
196
224
252
280
308
336
364
392
420
Copper
Aluminum
Silicon
Silver
Tin
Iron
Lead

Oil Consumption Data

Test time [hours]	Oil Consumed [lbs]	Cumulative Oil Consumption [lbs]
20	0.00	0.00
40	0.00	0.00
60	0.45	0.45
80	1.20	1.65
100	0.91	2.56
120	1.64	4.20
140	0.97	5.17
160	1.31	6.48
180	0.95	7.43
200	1.52	8.95
220	1.54	10.49
240	1.62	12.11
260	0.91	13.02
280	1.86	14.88
300	1.24	16.12
320	1.86	17.98
340	1.91	19.89
360	1.89	21.78
380	1.51	23.29
400	1.90	25.19

Oil level checks were preformed every 20 hours of test time at 20 minutes into the four-hour soak period and the oil sump level was restored to the test full mark using fresh oil

Average hourly oil consumption was 0.063 pounds per hour

Post Test Engine Condition and Deposits

Evaluation	Cylinder Number						
	1	2	3	4	5	6	Average
Piston Ring Sticking							
No. 1	None	None	None	None	None	None	
No. 2	None	None	None	None	None	Yes	
No. 3	None	None	None	None	None	None	
Scuffing, % Area							
No. 1 Ring	0	5	0	0	0	5	1.67
No. 2 Ring	0	0	0	0	0	5	0.83
No. 3 Ring	0	0	0	0	0	0	0.00
Piston	0	25	0	0	0	0	4.17
Cylinder	0	25	0	0	0	40	10.83
Piston Carbon Rating, Demerits							
No. 1 Groove	52.00	48.50	48.75	43.75	49.00	37.25	46.54
No. 2 Groove	10.00	3.00	2.00	2.25	3.75	6.00	4.50
No. 3 Groove	---	---	---	---	---	---	---
No. 1 Land	30.50	33.50	35.00	35.50	32.25	54.50	36.88
No. 2 Land	21.25	16.25	25.00	22.25	26.50	12.75	20.67
No. 3 Land	1.00	2.25	4.00	7.00	1.50	2.00	2.96
Cooling Gallery	---	---	---	---	---	---	---
Undercrown	---	---	---	---	---	---	---
Front Pin Bore	---	---	---	---	---	---	---
Rear Pin Bore	---	---	---	---	---	---	---
Piston Lacquer Rating, Demerits							
No. 1 Groove	---	---	---	---	---	---	---
No. 2 Groove	2.06	3.04	3.34	3.05	3.00	2.89	2.90
No. 3 Groove	3.00	2.93	3.58	3.68	2.50	2.75	3.07
No. 1 Land	0.11	0.08	0.18	0.00	0.36	0.18	0.15
No. 2 Land	1.29	0.59	1.22	1.19	1.40	1.91	1.27
No. 3 Land	4.07	3.66	3.44	2.71	3.73	2.69	3.38
No. 4 Land	2.70	2.50	2.50	2.36	2.40	2.30	2.46
Cooling Gallery	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Undercrown	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Front Pin Bore	---	---	---	---	---	---	---
Rear Pin Bore	---	---	---	---	---	---	---
Total Demerits (non-weighted)	131.0	119.3	132.0	126.7	129.4	128.2	127.8
Miscellaneous							
Top Groove Fill, %	44	40	42	40	40	24	38.3
Intermediate Groove Fill, %	1	0	0	0	1	1	0.5
Top Land Heavy Carbon, %	8	12	14	14	11	40	16.5
Top Land Flaked Cabon, %	0	0	0	0	0	0	0.0
Valve Tulip Deposits, merits							
Intake, Front	8.8	8.7	8.7	8.4	8.8	8.7	8.7
Intake, Rear	9.2	9.0	9.1	8.7	8.9	8.8	9.0
Intake, Average	9.0	8.9	8.9	8.6	8.9	8.8	8.8
Exhaust	8.0	8.0	8.0	8.0	8.0	8.0	8.0

Pre-Test Engine Rebuild Measurements

	Minimum	Maximum	Average	Specified Limits
Cylinder Bores				
Inside Diameter	4.3304	4.3327	4.3315	4.3307 - 4.3327
Out of Round	0.0000	0.0019	0.0010	0.0010 max
Taper	0.0007	0.0011	0.0009	
Piston Skirt Diameter	4.3269	4.3273	4.3271	
Piston Skirt to Cylinder Clearance	0.0041	0.0046	0.0043	0.0020 - 0.0050
Piston Ring End Gaps				
Top Ring	0.016	0.017	0.022	
Second Ring	0.049	0.052	0.046	
Oil Control Ring	0.023	0.024	0.023	
Piston Pin and Piston Pin Bore				
Piston Pin Diameter	1.5742	1.5744	1.5743	1.5743 - 1.5747
Piston Bore Diameter	1.5760	1.5762	1.5761	1.5757 - 1.5763
Piston Pin Clearance	0.0017	0.0019	0.0018	0.0010 - 0.0040
Clearances				
Connecting Rod Bearing to Journal	0.0020	0.0020	0.0020	0.0021 - 0.0061
Main Bearing to Journal	0.0020	0.0030	0.0026	0.0028 - 0.0068

Cylinder Bore Diameter Changes, in

Cylinder	Depth	Transverse (TD)	Longitude (LD)	Individual Cylinder Average Change
1	Top	0.0002	0.0002	
	Middle	0.0001	0.0000	0.0001
	Bottom	0.0001	0.0001	
2	Top	0.0004	0.0011	
	Middle	0.0005	0.0004	0.0006
	Bottom	0.0003	0.0009	
3	Top	0.0002	0.0002	
	Middle	0.0002	-0.0001	0.0001
	Bottom	-0.0001	0.0001	
4	Top	0.0003	0.0000	
	Middle	0.0002	-0.0001	0.0001
	Bottom	0.0001	0.0001	
5	Top	0.0003	0.0000	
	Middle	0.0003	0.0000	0.0001
	Bottom	0.0001	0.0001	
6	Top	0.0001	0.0010	
	Middle	0.0003	0.0006	0.0006
	Bottom	0.0001	0.0013	
Average Change for All Cylinders	Top	0.0003	0.0004	
	Middle	0.0003	0.0001	
	Bottom	0.0001	0.0004	

Overall average change: 0.0003

Top Ring Radial Wear, in.

Cylinder Number	Position	Before	After	Delta
1	1	0.11735	0.11735	0.00000
	2	0.11730	0.11730	0.00000
	3	0.11730	0.11730	0.00000
	4	0.11735	0.11735	0.00000
	5	0.11735	0.11735	0.00000
2	1	0.11710	0.11710	0.00000
	2	0.11725	0.11725	0.00000
	3	0.11735	0.11735	0.00000
	4	0.11735	0.11735	0.00000
	5	0.11715	0.11715	0.00000
3	1	0.11740	0.11740	0.00000
	2	0.11730	0.11730	0.00000
	3	0.11740	0.11740	0.00000
	4	0.11715	0.11715	0.00000
	5	0.11730	0.11730	0.00000
4	1	0.11735	0.11735	0.00000
	2	0.11715	0.11715	0.00000
	3	0.11710	0.11710	0.00000
	4	0.11730	0.11730	0.00000
	5	0.11725	0.11725	0.00000
5	1	0.11730	0.11730	0.00000
	2	0.11740	0.11740	0.00000
	3	0.11710	0.11710	0.00000
	4	0.11730	0.11730	0.00000
	5	0.11735	0.11735	0.00000
6	1	0.11730	0.11730	0.00000
	2	0.11745	0.11745	0.00000
	3	0.11725	0.11725	0.00000
	4	0.11730	0.11730	0.00000
	5	0.11730	0.11730	0.00000

maximum	0.00000
average	0.00000

Piston Ring Gap Measurements, in.

Cylinder Number	Ring No.	Before	After	Delta
1	1	0.017	0.016	-0.001
	2	0.051	0.048	-0.003
	3	0.024	0.021	-0.003
2	1	0.017	0.016	-0.001
	2	0.050	0.049	-0.001
	3	0.023	0.022	-0.001
3	1	0.017	0.016	-0.001
	2	0.052	0.051	-0.001
	3	0.024	0.021	-0.003
4	1	0.016	0.016	0.000
	2	0.050	0.049	-0.001
	3	0.023	0.021	-0.002
5	1	0.017	0.016	-0.001
	2	0.050	0.050	0.000
	3	0.024	0.021	-0.003
6	1	0.016	0.016	0.000
	2	0.049	0.048	-0.001
	3	0.023	0.021	-0.002

Ring No. 1 maximum increase	0.000
Ring No. 2 maximum increase	0.000
Ring No. 3 maximum increase	-0.001

Ring No. 1 average increase	-0.0007
Ring No. 2 average increase	-0.0012
Ring No. 3 average increase	-0.0023

Piston Ring Mass, grams

Cylinder Number	Ring No.	Before	After	Delta
1	1	28.6232	28.6071	0.0161
	2	26.6287	26.6236	0.0051
	3	16.7981	16.7917	0.0064
2	1	28.5471	28.5116	0.0355
	2	26.6572	26.6562	0.0010
	3	16.8319	16.8259	0.0060
3	1	28.5182	28.5097	0.0085
	2	26.6619	26.6570	0.0049
	3	16.8512	16.8388	0.0124
4	1	28.6266	28.6148	0.0118
	2	26.5550	26.5514	0.0036
	3	16.9677	16.9610	0.0067
5	1	28.5421	28.4993	0.0428
	2	26.4983	26.4943	0.0040
	3	16.8888	16.8807	0.0081
6	1	28.5611	28.5360	0.0251
	2	26.2921	26.2862	0.0059
	3	16.7859	16.7683	0.0176

Ring No. 1, maximum	0.0428
Ring No. 2, maximum	0.0059
Ring No. 3, maximum	0.0176

Ring No. 1, average	0.0233
Ring No. 2, average	0.0041
Ring No. 3, average	0.0095

Connecting Rod Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	75.5313	75.5101	0.0212
1B	75.6556	75.6443	0.0113
2T	75.5728	75.5530	0.0198
2B	75.4719	75.4687	0.0032
3T	75.4238	75.3998	0.0240
3B	75.4032	75.3924	0.0108
4T	75.3807	75.3698	0.0109
4B	75.4513	75.4472	0.0041
5T	75.3640	75.3459	0.0181
5B	75.4445	75.4418	0.0027
6T	75.4546	75.4415	0.0131
6B	75.4094	75.4053	0.0041

maximum	0.0240
average	0.0119

Main Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	73.4597	73.4550	0.0047
1B	80.0001	79.9968	0.0033
2T	73.4701	73.4658	0.0043
2B	79.9787	79.9763	0.0024
3T	73.4255	73.4224	0.0031
3B	80.0449	80.0418	0.0031
4T	73.5048	73.5029	0.0019
4B	79.9706	79.9684	0.0022
5T	73.4310	73.4258	0.0052
5B	79.9941	79.9918	0.0023
6T	141.6906	137.6885	4.0021
6B	81.0840	81.0830	0.0010
7T	73.5292	73.5266	0.0026
7B	79.9305	79.9261	0.0044

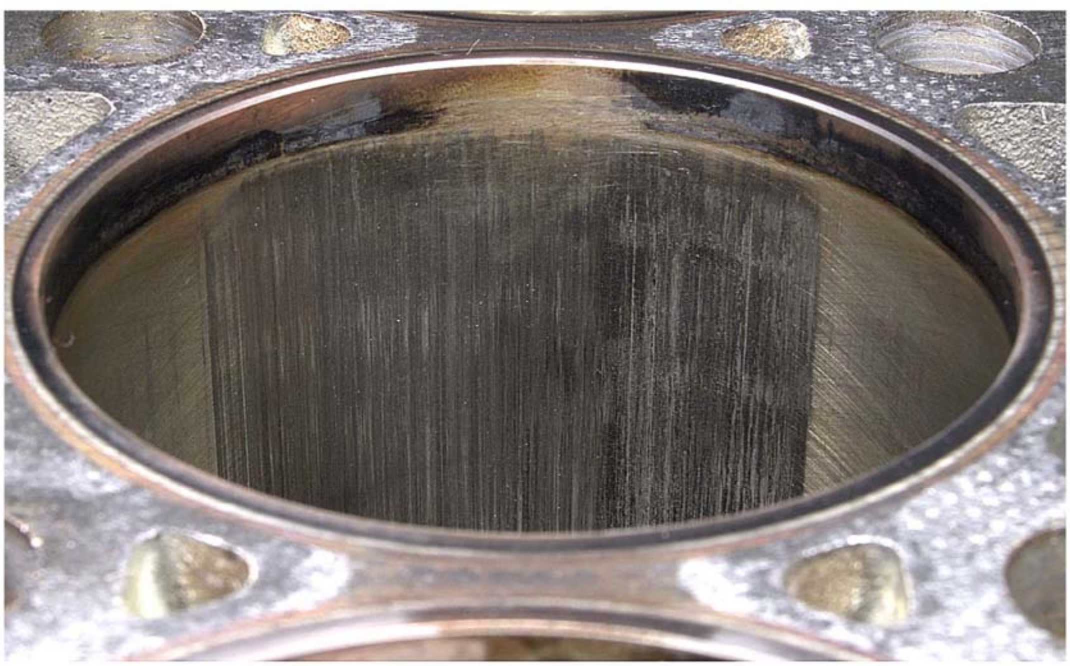
maximum	4.0021
average	0.2888

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Engine Block Cylinder Bore - Best Cyl. 3

Engine Block Cylinder Bore - Worst Cyl. 2



Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Piston Skirt Thrust - Best **Cyl. 3**

Piston Skirt Anti-thrust - Best **Cyl. 3**

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Piston Skirt Thrust - Worst **Cyl. 6**

Piston Skirt Anti-thrust - Worst **Cyl. 6**

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Piston Undercrown - Best **Cyl. 3**

Piston Undercrown - Worst **Cyl. 6**

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	EOT Date:	06-29-06
Test No.:	FMM03101-1A	Test Hours:	420

Intake and Exhaust Valve - Best Cyl. 1

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Intake and Exhaust Valve - Worst Cyl. 4

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

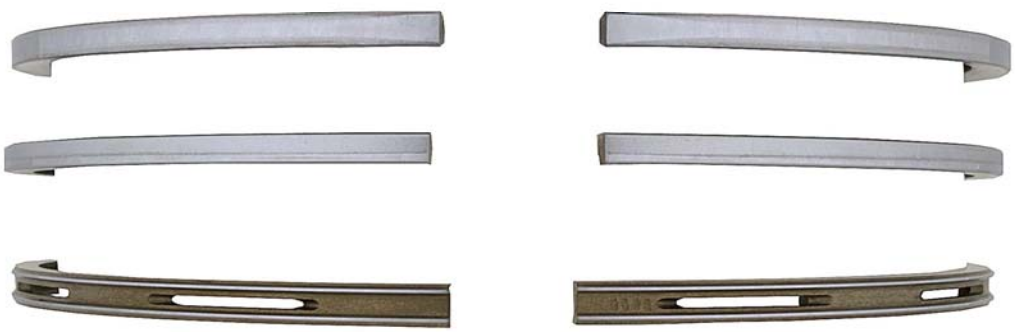
Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Crossheads - 1,2,3,4,5,6

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Piston Rings - Best **Cyl. 4**



Piston Rings - Worst **Cyl. 2**

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Main Bearings

Cat C7 - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	MIL-PRF-2104G SAE 15W40	**EOT Date:**	06-29-06
Test No.:	FMM03101-1A	**Test Hours:**	420

Rod Bearings

Appendix F

Test Fuel Properties

Table F-1. JP-8 Aviation Turbine Fuel Properties, AGE Refining

AGE REFINING, INC.

REFINING OFFICE:
7811 S. Presa
San Antonio, Texas 78223
(210) 532-5300
(210) 532-7222 Fax

Product Name: JP-8 MIL-DTL-83133E

Tank: 424
Batch: 2007J
Date: 03/03/07

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
		Min	Max	Results
Color, Saybolt	D 156		Report	+30
Total Acid, mg KOH/g	D 3242		0.015	0.009
Aromatics, vol%	D 1319		25	16.1
Olefins, vol%	D 1319		5.0	1.1
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg	-	Neg
Total Sulfur, mass%	D 2622		0.300	0.006
Distillation temperature, °C	D 86			
•IBP			Report	145
•10% recovered, temp			205	160
•20% recovered, temp			Report	166
•50% recovered, temp			Report	187
•90% recovered, temp			Report	239
•End Point, temp			300	262
•Residue, vol%			1.5	1.0
•Loss, vol%			1.5	1.0
Flash Point, °F	D 93	100		106
Gravity, API, at 15°C	D 1298	51.0	37.0	47.3
Freeze Point, °C	D 2386		-47	-48.60
Viscosity @ -20°C	D 445		8.0	3.06
Heat of combustion, BTU/lb	D 3338	18,400		18,643
Hydrogen content, mass%	D 3701	13.4		13.99
Smoke Point, mm	D 1322	19		26.0
Copper corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test @ 275 C	D 3241			1
• Pressure drop, mm Hg			25	0.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	0.6
Particulate matter, mg/L	D 5452		1	0.69
Filtration time, minutes	D 5452		15	5
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		92
Additives (Corrosion Inhibitor and Static Dissipator)				
Moisture, mg/Kg	D 6304		Report	51
Fuel System Icing Inhibitor	D 5006	0.10	0.15	0.125
Calculated Cetane Index	D 976		Report	42.4
SDA pS/m	D2624	150	450	

Report Date: 03/03/07

Analysis performed by: ____________________

Table F-2. ULSD 2007 Certification Diesel Fuel Properties, AL-27621

Certificate 3397673 Haltermann Products Page 1

Date: 03/15/2007 Certificate of Analysis

File Copy**GLOBAL**DO NOT EDIT
SOUTHWEST RESEARCH INSTITUTE Fax: COA ARCHIVE
6220 CULEBRA RD
SAN ANTONIO TX 78238-5166 UNITED STATES

Cust P.O.: 764932G Dlvy Note: 64029471 10
Cust Ref: Order No.: 21030941

Material: 2007 Certification Diesel
55 GALLON STEEL DRUM GMID: 229576

Cust Mtl:
Batch: UH2521LS10

Dlvy Qty:DR 7
Vehicle: SH

Ship from: JOHANN HALTERMANN LTD DEER PARK TX UNITED STATES

Feature	Units	Results UH2521LS10	Limits Minimum	Limits Maximum	Method
Distillation-IBP	degF	377	340	400	ASTM D86
Distillation-5%	degF	407	----	----	ASTM D86
Distillation-10%	degF	417	400	460	ASTM D86
Distillation-20%	degF	438	----	----	ASTM D86
Distillation-30%	degF	456	----	----	ASTM D86
Distillation-40%	degF	478	----	----	ASTM D86
Distillation-50%	degF	500	470	540	ASTM D86
Distillation-60%	degF	520	----	----	ASTM D86
Distillation-70%	degF	541	----	----	ASTM D86
Distillation-80%	degF	564	----	----	ASTM D86
Distillation-90%	degF	592	560	630	ASTM D86
Distillation-95%	degF	618	----	----	ASTM D86
Distillation-EP	degF	638	610	690	ASTM D86
Recovery	% vol	97.4	----	----	ASTM D86
Residue	% vol	2.1	----	----	ASTM D86
Loss	% vol	0.0	----	----	ASTM D86
Gravity, API	-	35.2	32.0	37.0	ASTM D4052
Specific Gravity	kg/L	0.849	0.840	0.865	ASTM D4052
Sulfur	ppm	10	7	15	ASTM D5453

Business Quality Leader
Dow Haltermann

For inquiries please contact Customer Service or local sales.

Table F-2. (continued)

Certificate 3397673 Haltermann Products Page 2

Date: 03/15/2007 Certificate of Analysis

File Copy**GLOBAL**DO NOT EDIT
SOUTHWEST RESEARCH INSTITUTE Fax: COA ARCHIVE
6220 CULEBRA RD
SAN ANTONIO TX 78238-5166 UNITED STATES

Cust P.O.: 764932G Dlvy Note: 64029471 10
Cust Ref: Order No.: 21030941

Material: 2007 Certification Diesel
55 GALLON STEEL DRUM GMID: 229576

Cust Mtl:

Dlvy Qty:DR 7
Vehicle: SH

Ship from: JOHANN HALTERMANN LTD DEER PARK TX UNITED STATES

Feature	Units	Results UH2521LS10	Limits Minimum	Limits Maximum	Method
Flash Point	degF	170	130	----	ASTM D93
Carbon	% wt	86.000	----	----	ASTM D5291
Hydrogen	% wt	14.000	----	----	ASTM D5291
Viscosity	cSt	2.5	2.0	3.2	ASTM D445
Aromatics	% vol	29.5	27.0	----	ASTM D1319
Olefins	% vol	1.0	----	----	ASTM D1319
Saturates	% vol	69.5	----	----	ASTM D1319
Cetane Number	-	44.4	40.0	50.0	ASTM D613
Cetane Index	-	50.0	40.0	50.0	ASTM D976
Net Heating Value	Btu/lb	18,493	----	----	ASTM D240
High Freg. Recip. R @ 60degC	mm	0.061	----	----	ASTM D6079

Table F-3. 1:1 Blend Ratio of S-8 Synthetic Fuel and JP-8 Aviation Turbine Fuel Properties, AL-27735

Property	Units	Method	Results
Distillation	**°C @ vol% rec.**	**ASTM D 86**	
	IBP		145
	10		161
	20		168
	30		176
	40		184
	50		192
	60		213
	70		202
	80		225
	90		240
	95		251
	FBP		259
	Residue		1.7
	Loss		1.6
Flash Point	°C	ASTM D 3858	37
Freezing point	°C	ASTM D 2386	-52
Sulfur	ppm	ASTM D 5453	46
Density @ 15°C	kg/m^3	ASTM D 4052	773.9
Color, Saybolt	Visual rating	ASTM D 156	+24
Cetane Number	—	ASTM D 613	54
Kinematic Vis @ –20°C	mm^2/s	ASTM D 445	3.72[a]
Net Heat of Combustion	BTU/lb	ASTM D 240	18,632
a = calculated value			

Appendix G

FISCHER TROPSCH SYNTHETIC FUEL EVALUATIONS

WORK DIRECTIVE NO. 23

Caterpillar C7

Test Lubricant: AL-27170-L
Army Reference Oil, MIL-PRF-2104G, SAE 15W40
Test Fuel: Fischer-Tropsch S-8, AL-27755
Test Number: FMM03100-4A
Start of Test Date: 8 May 2007
End of Test Date: 24 August 2007
Test Duration: 420 Hours
Test Procedure: Extended Tactical Wheeled Vehicle

Conducted For

U.S. Army RDECOM
Tank-Automotive Research, Development & Engineering Center
Petroleum and Water Business Area
Warren, Michigan 48397-5000

By

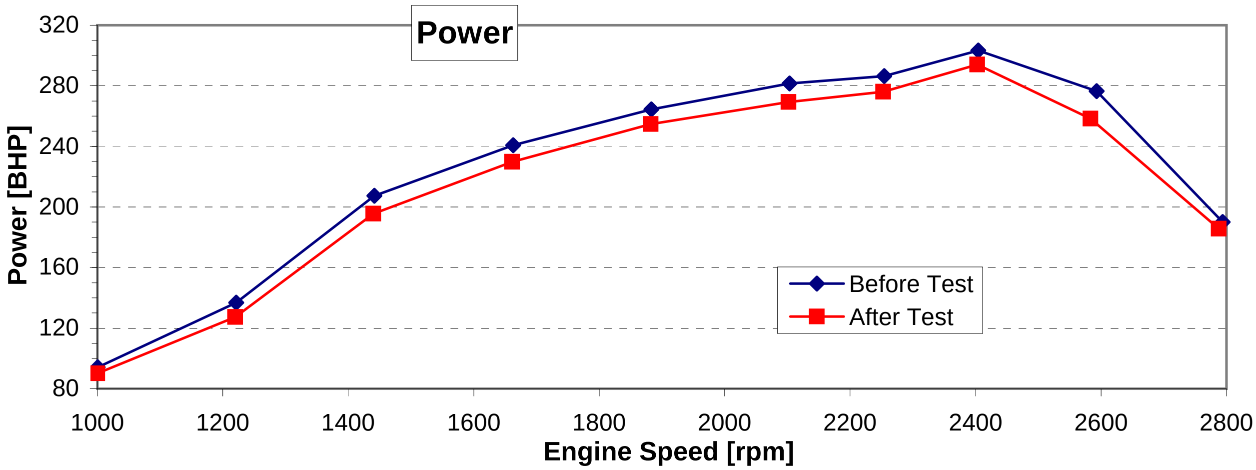
TARDEC Fuel and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

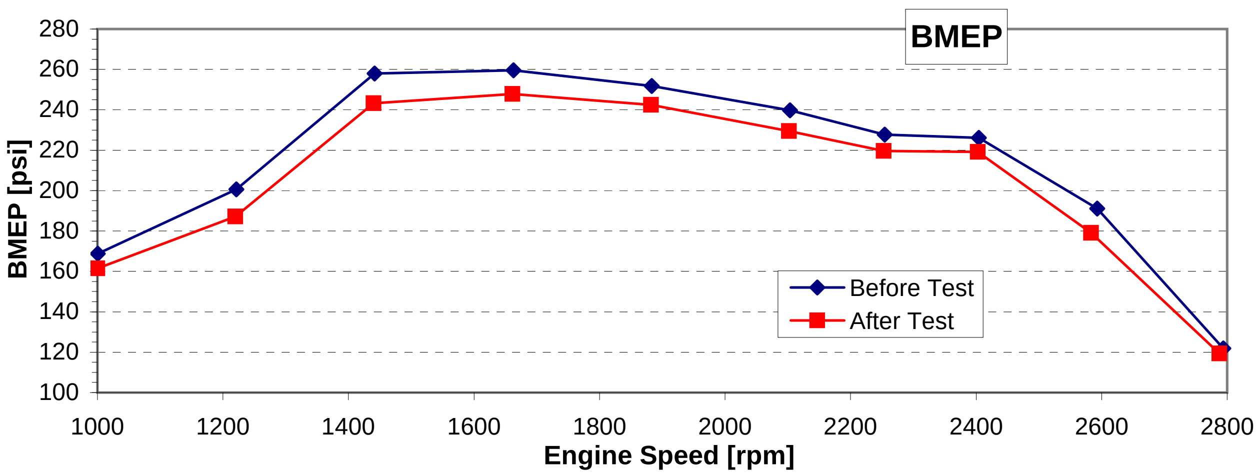
Contract DAAE07-99-C-L053

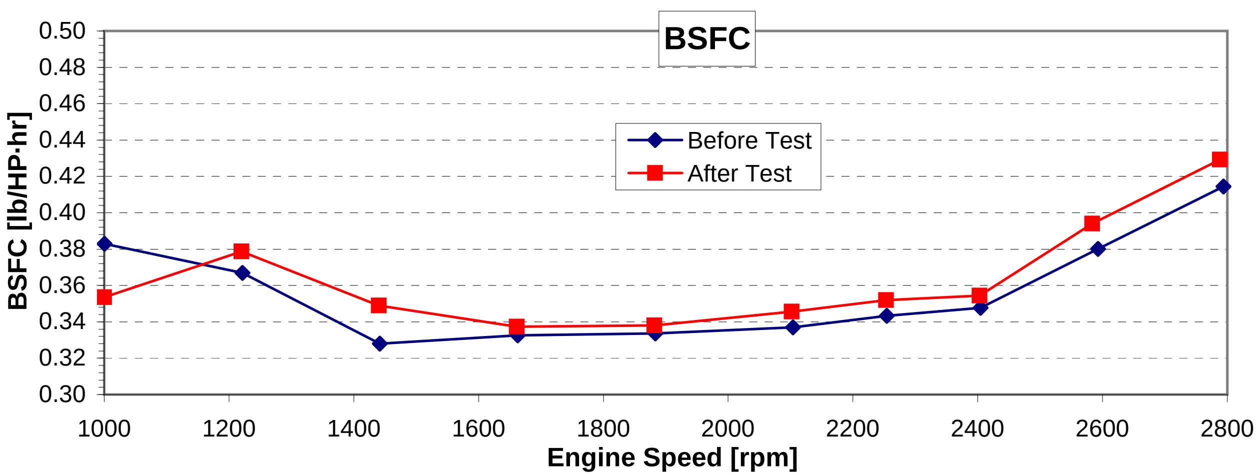
Engine Operating Conditions Summary

	Maximum Power Mode (2400 rpm)		Idle Mode (750 rpm)	
	Mean	Std. Dev.	Mean	Std. Dev.
Performance				
Engine Speed [rpm]	2400.0	0.3	750.0	0.7
Torque [ft·lb]	637.7	11.7	4.8	0.6
Fuel Consumption [lb/hr]	103.9	1.6	2.3	0.1
Observed Power [Bhp]	291.4	6.1	0.7	0.1
BSFC [lb/Bhp·hr]	0.357	0.011	3.392	0.708
Temperatures [°F]				
Oil Sump	259.6	0.5	195.9	0.9
Water Jacket Inlet	208.4	1.4	188.7	0.5
Water Jacket Outlet	217.1	0.9	190.0	0.3
Fuel Inlet to Pump	121.5	2.2	112.5	6.7
Fuel Return	177.2	1.4	170.9	2.7
Inlet Air	98.1	4.7	90.9	4.8
Intake Manifold Air	140.0	3.2	86.8	1.7
Exhaust Port Cylinder 1	938.8	14.6	223.2	5.4
Exhaust Port Cylinder 2	1086.6	12.6	245.1	11.0
Exhaust Port Cylinder 3	1091.7	10.8	241.1	14.1
Exhaust Port Cylinder 4	1064.0	13.0	227.1	5.0
Exhaust Port Cylinder 5	1073.7	11.9	216.7	26.5
Exhaust Port Cylinder 6	1021.2	8.9	235.8	11.7
Exhaust, Front Before Turbo	1137.4	12.3	246.4	11.7
Exhaust, Rear Before Turbo	1134.9	10.4	234.2	5.7
Exhaust After Turbo	871.1	12.4	227.8	5.1
Pressures				
Oil [psi]	44.6	0.7	29.2	0.4
Barometer [psiA]	14.2	0.1	14.2	0.1
Intake Before Compressor [psiA]	13.3	0.0	14.2	0.1
Intake After Compressor [psiA]	42.6	0.1	14.3	0.1
Exhaust Before Turbo [psig]	27.4	1.3	0.3	0.1
Exhaust After Turbo [psig]	28.3	0.4	-0.1	0.2
Emissions				
CO [ppm]	428	25.1	---	---
CO_2 [%]	7.56	0.10	---	---
HC [ppm]	80.8	1.8	---	---
NO_X [ppm]	452	16.4	---	---
O_2 [%]	10.5	0.13	---	---
Smoke [% opacity]	0.1	0.06	---	---

Engine Performance Curves







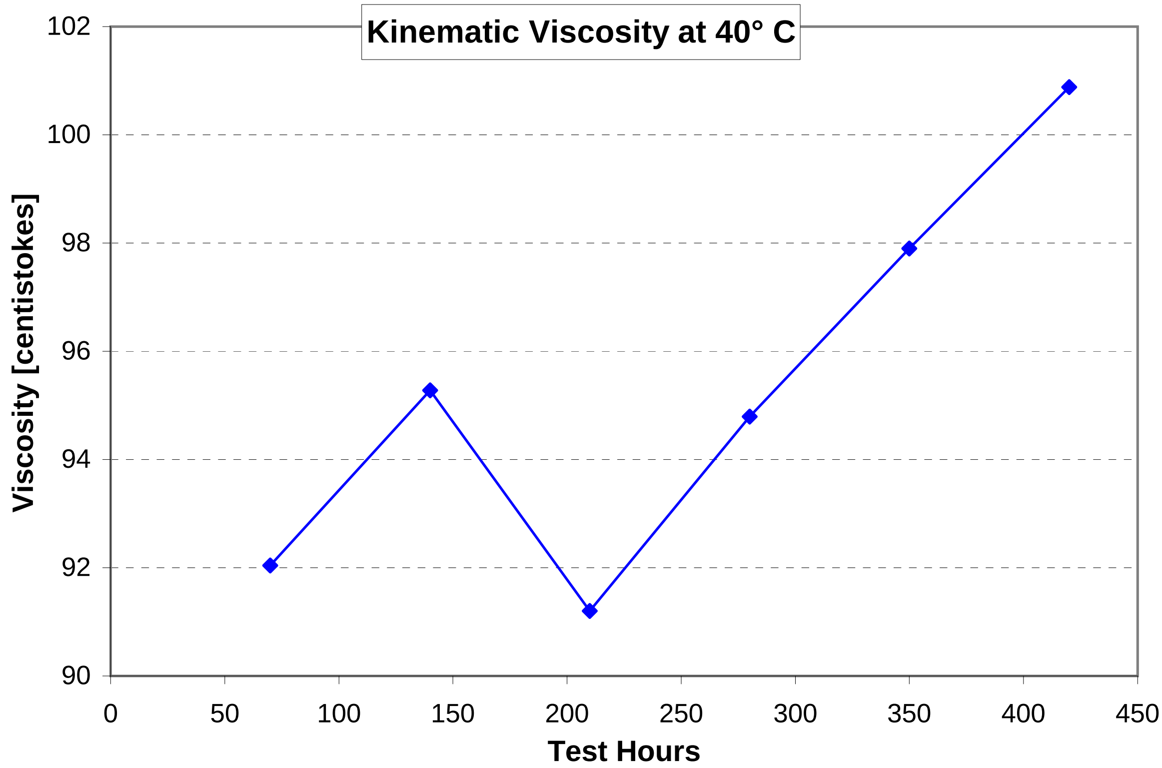
Emissions Data

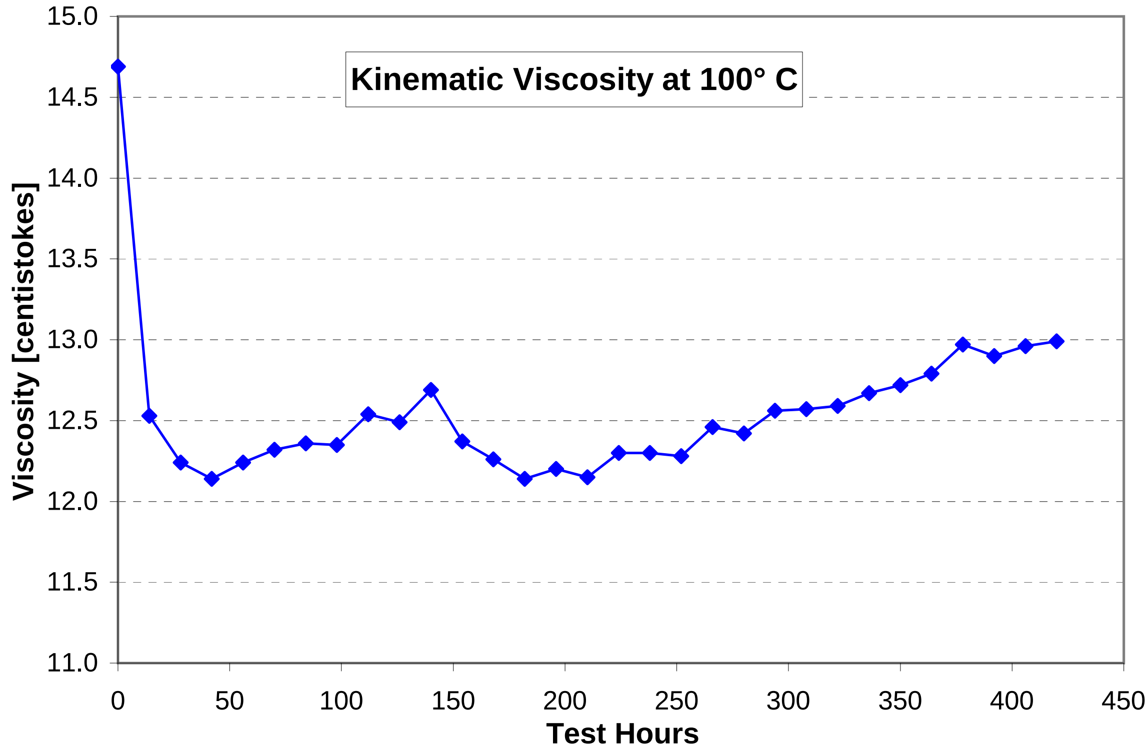
Test Hours	Smoke [% opacity]	NO_X [ppm]	O_2 [%]	CO_2 [%]	CO [ppm]	HC [ppm]
1	0.1	435	10.69	7.39	403	79.8
15	0.1	449	10.51	7.51	396	83.0
29	0.0	452	10.63	7.43	390	84.6
43	0.0	456	10.48	7.54	387	82.7
57	0.1	455	10.48	7.55	390	81.7
71	0.0	453	10.50	7.53	392	82.6
85	0.1	457	10.54	7.50	403	79.6
99	0.1	471	10.21	7.73	407	75.9
113	0.1	452	10.31	7.67	411	80.2
127	0.1	443	10.41	7.59	411	78.6
141	0.1	453	10.34	7.64	426	79.7
155	0.0	456	10.36	7.63	419	79.0
169	0.1	460	10.30	7.67	424	79.8
183	0.1	460	10.35	7.66	422	79.3
197	0.1	466	10.38	7.62	421	79.1
211	0.2	463	10.23	7.72	433	79.7
225	0.2	452	10.41	7.59	441	82.7
239	0.1	455	10.34	7.64	451	80.5
253	0.1	471	10.38	7.62	445	81.2
267	0.0	434	10.47	7.55	441	80.9
281	0.2	501	10.47	7.55	433	81.7
295	0.1	448	10.30	7.67	465	79.9
309	0.0	460	10.46	7.56	436	81.0
323	0.1	442	10.53	7.51	433	79.4
337	0.0	462	10.58	7.47	435	80.2
351	0.1	436	10.60	7.46	462	81.3
365	0.1	402	10.76	7.34	458	80.9
379	0.1	451	10.46	7.56	467	82.0
393	0.1	438	10.36	7.63	475	83.1
407	0.1	438	10.66	7.41	450	83.2
Minimum	0	402	10.21	7.34	387	75.9
Maximum	0.2	501	10.76	7.73	475	84.6
Average	0.1	452	10.45	7.56	428	80.8
Standard Deviation	0.06	16.4	0.135	0.098	25.1	1.8

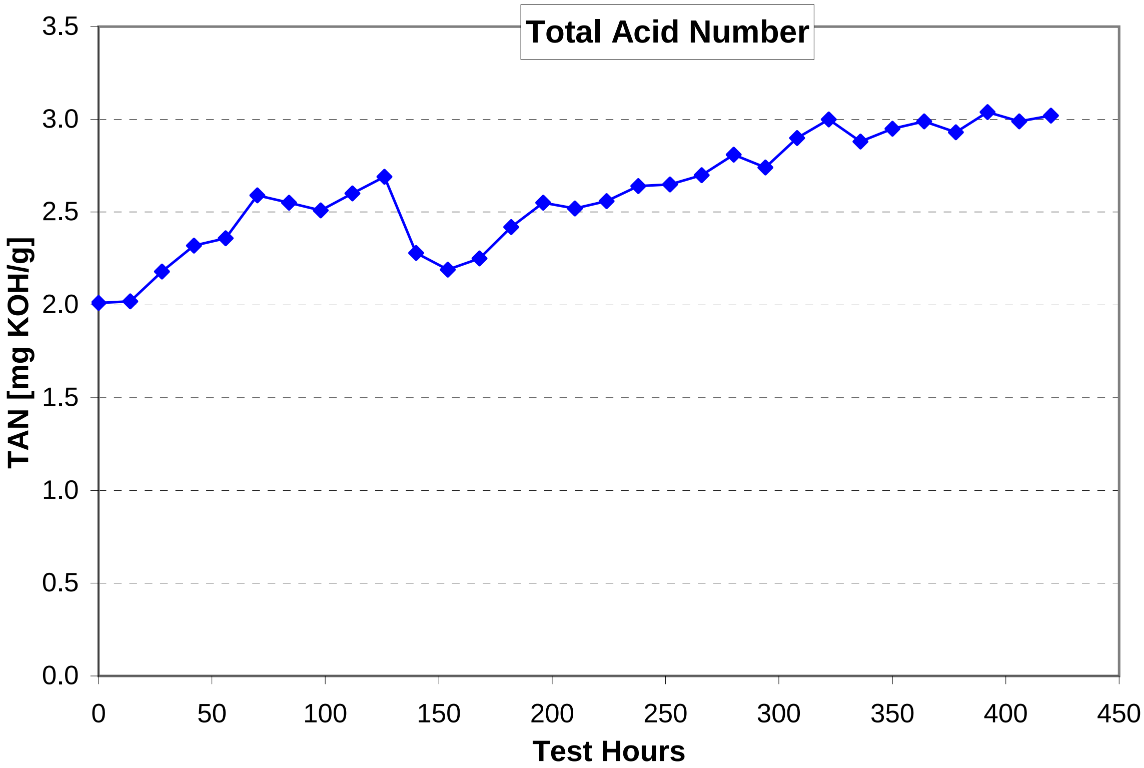
Lubricant Analysis

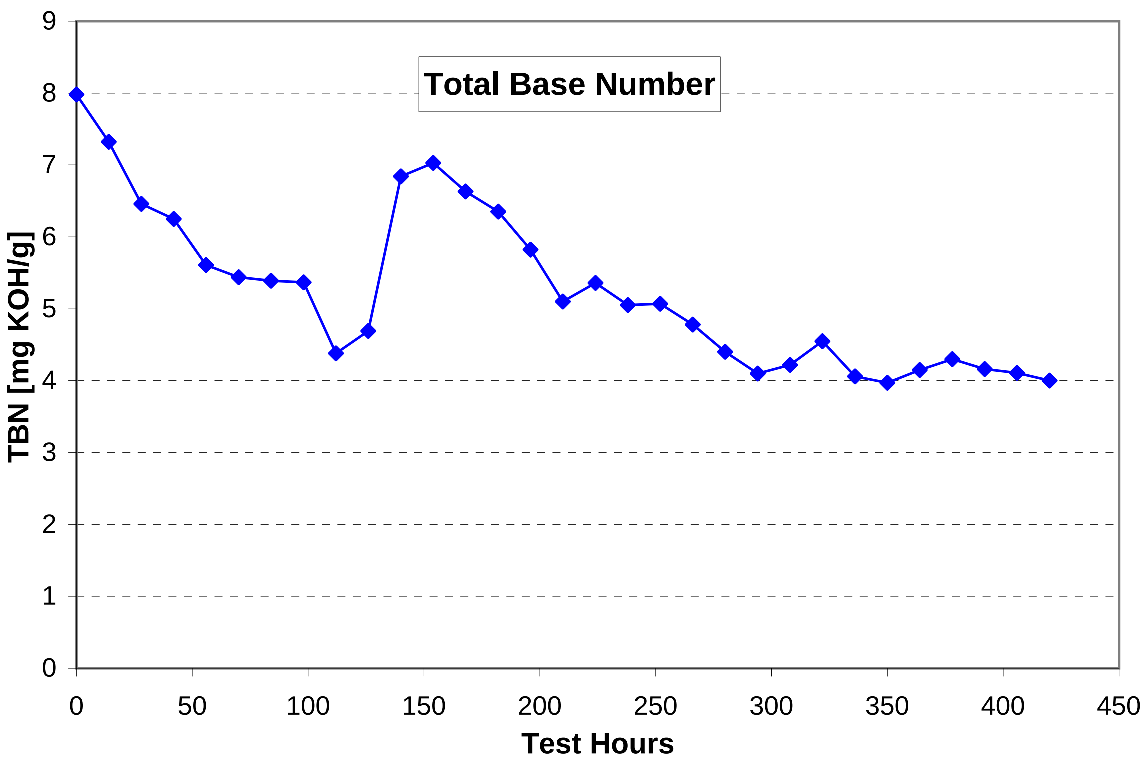
	0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210
Total Base Number [mg KOH/g] (ASTM D664)	7.98	7.32	6.46	6.25	5.61	5.44	5.39	5.37	4.38	4.69	6.84	7.03	6.63	6.35	5.82	5.10
Total Acid Number [mg KOH/g] (ASTM D4739)	2.01	2.02	2.18	2.32	2.36	2.59	2.55	2.51	2.60	2.69	2.28	2.19	2.25	2.42	2.55	2.52
Kinematic Viscosity at 100°C (212°F) [cSt] (ASTM D445)	14.69	12.53	12.24	12.14	12.24	12.32	12.36	12.35	12.54	12.49	12.69	12.37	12.26	12.14	12.20	12.15
Kinematic Viscosity at 40°C (104°F) [cSt] (ASTM D445)		---	---	---	---	92.04	---	---	---	---	95.28	---	---	---	---	91.20
Viscosity Index (ASTM D2270)		---	---	---	---	128	---	---	---	---	129	---	---	---	---	126
API Gravity (ASTM D4052)		27.9	27.7	27.7	27.6	27.6	27.4	27.6	27.8	27.3	27.5	27.9	27.8	27.7	27.6	27.6
Density (ASTM D4052)	0.8872	0.8870	0.8877	0.8878	0.8886	0.8888	0.8895	0.8884	0.8872	0.8911	0.8870	0.8869	0.8874	0.8879	0.8883	0.8887
Soot (TGA)		0.247	0.240	0.252	0.276	0.281	0.318	0.246	0.311	0.324	0.137	0.284	0.274	0.283	0.306	0.207
Oxidation [Abs./cm] (ASTM E168)		-0.02	0.88	1.84	2.32	3.26	3.65	4.38	4.54	5.35	1.24	0.70	1.20	2.07	2.63	3.05
Nitration [Abs./cm] (ASTM E168)		0.18	0.37	0.37	0.46	0.46	0.46	0.37	0.37	0.37	0.18	0.18	0.37	0.46	0.46	0.46
Wear Metals by ICP, ppm (ASTM D5185)																
Iron		4	6	7	8	10	11	12	12	13	6	5	7	8	9	10
Copper		2	3	3	3	4	4	4	4	4	1	2	2	2	2	3
Aluminum		-	1	1	1	1	2	1	2	1	1	-	1	1	1	1
Silicon		5	8	6	7	8	8	7	7	8	4	3	3	3	4	3
Silver		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tin		-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Lead		-	-	-	-	1	1	2	2	2	-	-	-	-	-	-

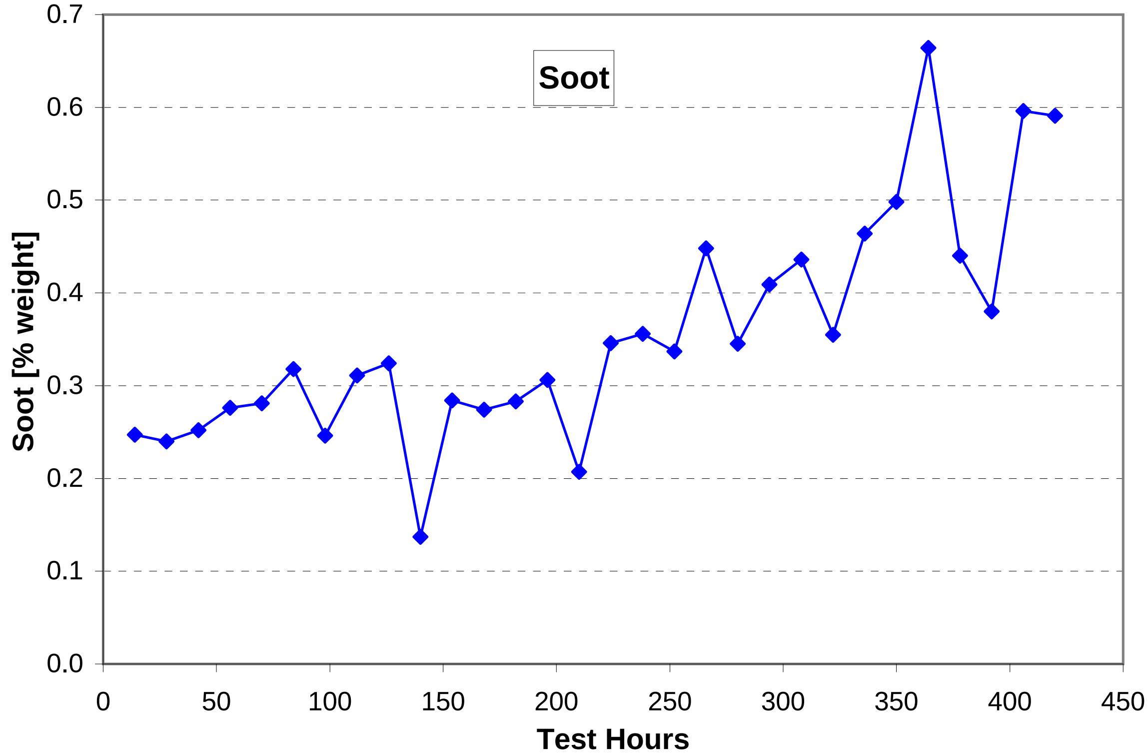
Test Hours	224	238	252	266	280	294	308	322	336	350	364	378	392	406	420
Total Base Number [mg KOH/g] (ASTM D664)	5.36	5.05	5.07	4.78	4.40	4.10	4.22	4.55	4.06	3.97	4.15	4.30	4.16	4.11	4.00
Total Acid Number [mg KOH/g] (ASTM D4739)	2.56	2.64	2.65	2.70	2.81	2.74	2.90	3.00	2.88	2.95	2.99	2.93	3.04	2.99	3.02
Kinematic Viscosity at 100°C (212°F) [cSt] (ASTM D445)	12.30	12.30	12.28	12.46	12.42	12.56	12.57	12.59	12.67	12.72	12.79	12.97	12.90	12.96	12.99
Kinematic Viscosity at 40°C (104°F) [cSt] (ASTM D445)	---	---	---	---	94.79	---	---	---	---	97.90	---	---	---	---	100.88
Viscosity Index (ASTM D2270)	---	---	---	---	125	---	---	---	---	125	---	---	---	---	125
API Gravity (ASTM D4052)	27.5	27.4	27.4	27.2	27.2	27.1	27.2	27.1	27.0	27.0	26.9	26.9	26.8	26.9	26.9
Density (ASTM D4052)	0.8890	0.8895	0.8898	0.8906	0.8909	0.8911	0.8910	0.8913	0.8916	0.8919	0.8926	0.8924	0.8928	0.8927	0.8927
Soot (TGA)	0.346	0.356	0.337	0.448	0.345	0.409	0.436	0.355	0.464	0.498	0.664	0.440	0.380	0.596	0.591
Oxidation [Abs./cm] (ASTM E168)	3.48	4.21	4.79	5.18	5.81	6.09	6.64	7.01	7.84	8.30	8.86	8.86	9.50	9.50	10.42
Nitration [Abs./cm] (ASTM E168)	0.55	0.55	0.55	0.55	0.46	0.46	0.46	0.46	0.37	0.37	0.28	0.18	0.18	0.18	0.28
Wear Metals by ICP, ppm (ASTM D5185)															
Iron	11	12	13	14	14	15	16	16	17	18	19	18	20	20	20
Copper	3	3	3	3	4	4	4	4	4	5	5	5	6	6	7
Aluminum	1	1	1	2	2	3	2	3	2	2	2	2	2	2	2
Silicon	2	4	2	4	4	4	4	5	5	5	4	5	5	5	5
Silver	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tin	-	-	-	-	-	-	1	1	1	1	1	1	1	1	1
Lead	-	1	2	2	2	2	2	2	2	2	3	3	3	3	3

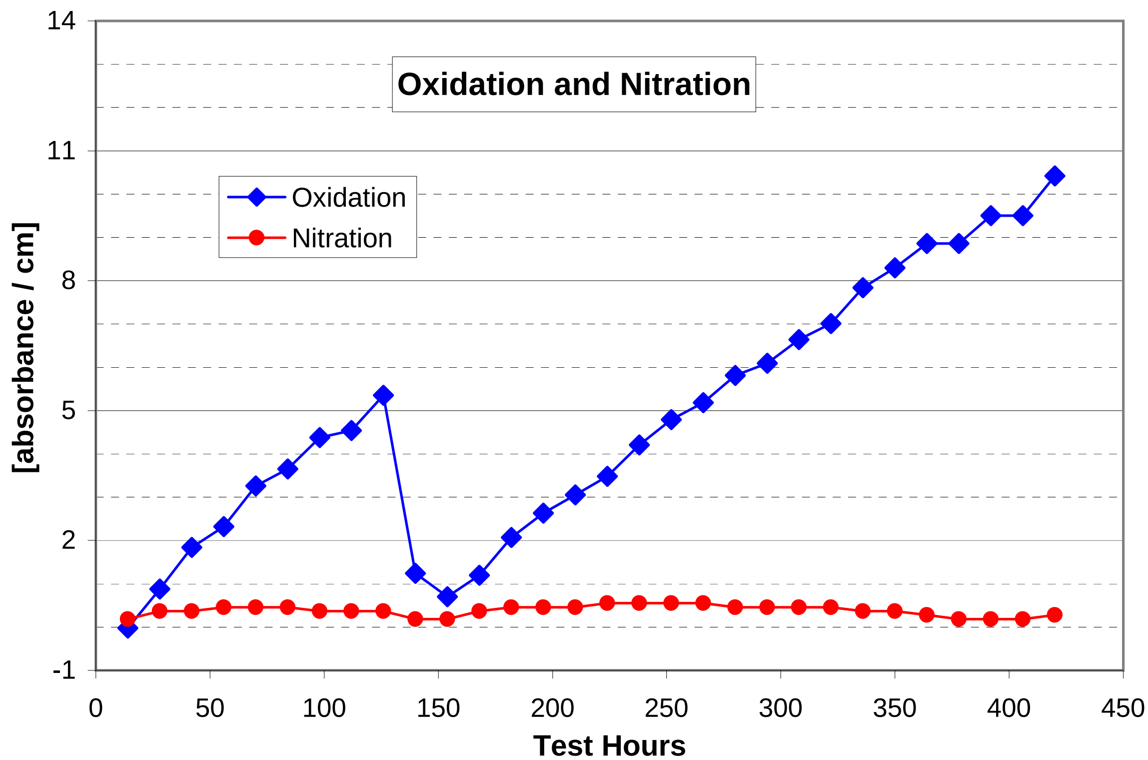

Kinematic Viscosity at 40° C
Viscosity [centistokes]
102
100
98
96
94
92
90
0
50
100
150
200
250
300
350
400
450
Test Hours

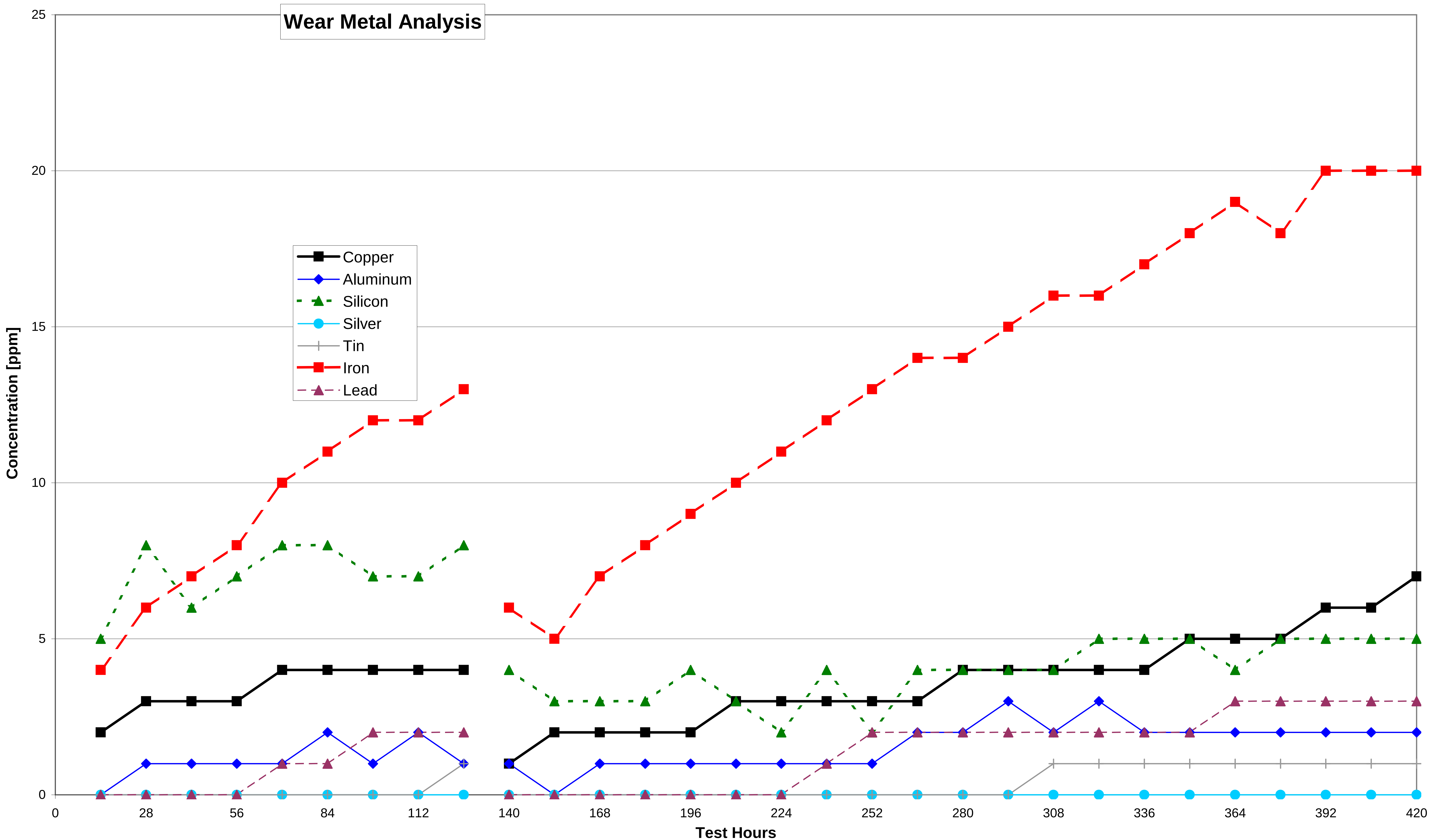

Kinematic Viscosity at 100° C
Viscosity [centistokes]
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
0
50
100
150
200
250
300
350
400
450
Test Hours


Total Acid Number
TAN [mg KOH/g]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
450
Test Hours


Total Base Number
TBN [mg KOH/g]
9
8
7
6
5
4
3
2
1
0
0
50
100
150
200
250
300
350
400
450
Test Hours


Soot
Soot [% weight]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
50
100
150
200
250
300
350
400
450
Test Hours


Oxidation and Nitration
Oxidation
Nitration
[absorbance / cm]
-1
2
5
8
11
14
0
50
100
150
200
250
300
350
400
450
Test Hours


Wear Metal Analysis
Copper
Aluminum
Silicon
Silver
Tin
Iron
Lead
Concentration [ppm]
Test Hours
0
5
10
15
20
25
0
28
56
84
112
140
168
196
224
252
280
308
336
364
392
420

Oil Consumption Data

Test time [hours]	Oil Consumed [lbs]	Cumulative Oil Consumption [lbs]
14	0.00	0.00
28	0.00	0.00
42	1.66	1.66
56	1.78	3.44
70	1.66	5.09
84	1.81	6.91
98	1.81	8.72
112	1.81	10.53
126	1.81	12.34
140		12.34
154	1.26	13.60
168	1.53	15.13
182	1.86	16.99
196	1.55	18.54
210	1.59	20.13
224	1.26	21.39
238	1.26	22.65
252	1.55	24.20
266	1.24	25.44
280	1.85	27.29
294	1.26	28.55
308	1.87	30.42
322	0.96	31.38
336	0.98	32.36
350	1.25	33.61
364	1.58	35.19
378	1.61	36.80
392	1.60	38.40
406	1.58	39.98

Oil level checks were preformed every 20 hours of test time at 20 minutes into the four-hour soak period and the oil sump level was restored to the test full mark using fresh oil

Average hourly oil consumption was 0.098 pounds per hour

Post Test Engine Condition and Deposits

Evaluation	Cylinder Number						
	1	2	3	4	5	6	Average
Piston Ring Sticking							
No. 1	None	None	None	None	None	None	
No. 2	None	None	None	None	None	None	
No. 3	None	None	None	None	None	None	
Scuffing, % Area							
No. 1 Ring	0	0	0	0	0	0	0.00
No. 2 Ring	0	0	0	0	0	0	0.00
No. 3 Ring	0	0	0	0	0	0	0.00
Piston	0	0	0	0	0	0	0.00
Cylinder	0	0	0	0	0	0	0.00
Piston Carbon Rating, Demerits							
No. 1 Groove	40.75	45.00	30.00	31.25	27.75	26.75	33.58
No. 2 Groove	18.00	11.75	12.25	15.00	11.25	12.00	13.38
No. 3 Groove	---	---	---	---	---	---	---
No. 1 Land	26.00	26.00	23.00	25.00	26.25	28.25	25.75
No. 2 Land	31.75	44.75	31.75	30.00	28.25	38.75	34.21
No. 3 Land	0.00	0.00	0.00	0.00	0.00	1.50	0.25
Cooling Gallery	---	---	---	---	---	---	---
Undercrown	---	---	---	---	---	---	---
Front Pin Bore	---	---	---	---	---	---	---
Rear Pin Bore	---	---	---	---	---	---	---
Piston Lacquer Rating, Demerits							
No. 1 Groove	0.15	0.00	0.00	0.00	0.00	0.00	0.03
No. 2 Groove	1.78	2.78	1.93	1.92	2.06	1.94	2.07
No. 3 Groove	3.02	3.14	2.62	4.63	3.22	3.10	3.29
No. 1 Land	0.15	0.09	0.56	0.41	0.05	0.18	0.24
No. 2 Land	0.85	0.36	0.32	0.42	0.37	0.36	0.45
No. 3 Land	3.87	3.89	2.86	4.47	4.64	4.16	3.98
No. 4 Land	3.07	3.20	3.20	3.10	3.02	2.80	3.07
Cooling Gallery	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Undercrown	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Front Pin Bore	---	---	---	---	---	---	---
Rear Pin Bore	---	---	---	---	---	---	---
Total Demerits (non-weighted)	132.4	144.0	111.5	119.2	109.9	122.8	123.3
Miscellaneous							
Top Groove Fill, %	27	40	14	18	12	10	20.2
Intermediate Groove Fill, %	2	1	2	2	1	2	1.7
Top Land Heavy Carbon, %	2	2	0	2	2	5	2.2
Top Land Flaked Cabon, %	0	0	0	0	0	0	0.0
Valve Tulip Deposits, merits							
Intake, Front	7.5	7.5	8.5	8.0	8.0	8.8	8.1
Intake, Rear	7.4	7.5	8.4	8.0	8.4	8.5	8.0
Intake, Average	7.5	7.5	8.5	8.0	8.2	8.7	8.0
Exhaust	7.8	8.0	8.0	7.8	7.8	8.8	8.0

Pre-Test Engine Rebuild Measurements

	Minimum	Maximum	Average	Specified Limits
Cylinder Bores				
Inside Diameter	4.3310	4.3333	4.3320	4.3307 - 4.3327
Out of Round	0.0001	0.0020	0.0010	0.0010 max
Taper	0.0002	0.0008	0.0005	
Piston Skirt Diameter	4.3270	4.3275	4.3274	
Piston Skirt to Cylinder Clearance	0.0039	0.0043	0.0041	0.0020 - 0.0050
Piston Ring End Gaps				
Top Ring	0.017	0.018	0.025	
Second Ring	0.048	0.061	0.051	
Oil Control Ring	0.018	0.020	0.019	
Piston Pin and Piston Pin Bore				
Piston Pin Diameter	1.5744	1.5744	1.5744	1.5743 - 1.5747
Piston Bore Diameter	1.5761	1.5762	1.5762	1.5757 - 1.5763
Piston Pin Clearance	0.0017	0.0018	0.0018	0.0010 - 0.0040
Clearances				
Connecting Rod Bearing to Journal	0.0020	0.0020	0.0020	0.0021 - 0.0061
Main Bearing to Journal	0.0040	0.0040	0.0040	0.0028 - 0.0068

Cylinder Bore Diameter Changes, in.

Cylinder	Depth	Transverse (TD)	Longitude (LD)	Individual Cylinder Average Change
1	Top	0.0001	-0.0007	
	Middle	0.0000	-0.0017	-0.0006
	Bottom	-0.0004	-0.0010	
2	Top	0.0001	-0.0015	
	Middle	0.0007	-0.0032	-0.0009
	Bottom	0.0004	-0.0018	
3	Top	0.0001	-0.0015	
	Middle	0.0005	-0.0033	-0.0010
	Bottom	-0.0001	-0.0018	
4	Top	0.0002	-0.0008	
	Middle	0.0008	-0.0021	-0.0005
	Bottom	0.0002	-0.0011	
5	Top	0.0009	-0.0013	
	Middle	0.0014	-0.0027	-0.0004
	Bottom	0.0003	-0.0012	
6	Top	0.0001	-0.0002	
	Middle	0.0002	-0.0010	-0.0003
	Bottom	-0.0003	-0.0008	
Average Change for All Cylinders	Top	0.0002	-0.0010	
	Middle	0.0006	-0.0023	
	Bottom	0.0000	-0.0013	

Overall average change: -0.0006

Top Ring Radial Wear, in.

Cylinder Number	Position	Before	After	Change
1	1	0.17260	0.17185	0.00075
	2	0.17085	0.17080	0.00005
	3	0.17255	0.17230	0.00025
	4	0.17415	0.17415	0.00000
	5	0.17320	0.17320	0.00000
2	1	0.17180	0.17130	0.00050
	2	0.17110	0.17110	0.00000
	3	0.17165	0.17165	0.00000
	4	0.17250	0.17220	0.00030
	5	0.17155	0.17125	0.00030
3	1	0.17375	0.17290	0.00085
	2	0.17195	0.17190	0.00005
	3	0.17370	0.17370	0.00000
	4	0.17415	0.17375	0.00040
	5	0.17285	0.17275	0.00010
4	1	0.17255	0.17235	0.00020
	2	0.17170	0.17160	0.00010
	3	0.17285	0.17270	0.00015
	4	0.17380	0.17370	0.00010
	5	0.17270	0.17260	0.00010
5	1	0.17200	0.17200	0.00000
	2	0.17275	0.17270	0.00005
	3	0.17365	0.17360	0.00005
	4	0.17315	0.17295	0.00020
	5	0.17230	0.17230	0.00000
6	1	0.17205	0.17205	0.00000
	2	0.17280	0.17280	0.00000
	3	0.17410	0.17395	0.00015
	4	0.17360	0.17345	0.00015
	5	0.17220	0.17220	0.00000

maximum	0.00085
average	0.00016

Piston Ring Gap Measurements, in.

Cylinder Number	Ring No.	Before	After	Change
1	1	0.017	0.015	-0.002
	2	0.048	0.046	-0.002
	3	0.018	0.016	-0.002
2	1	0.017	0.015	-0.002
	2	0.061	0.058	-0.003
	3	0.018	0.016	-0.002
3	1	0.018	0.015	-0.003
	2	0.061	0.058	-0.003
	3	0.020	0.016	-0.004
4	1	0.017	0.015	-0.002
	2	0.060	0.058	-0.002
	3	0.019	0.016	-0.003
5	1	0.018	0.015	-0.003
	2	0.060	0.058	-0.002
	3	0.019	0.016	-0.003
6	1	0.018	0.015	-0.003
	2	0.060	0.058	-0.002
	3	0.019	0.016	-0.003

Ring No. 1 maximum increase	-0.002
Ring No. 2 maximum increase	-0.002
Ring No. 3 maximum increase	-0.002

Ring No. 1 average increase	-0.0025
Ring No. 2 average increase	-0.0023
Ring No. 3 average increase	-0.0028

Piston Ring Mass, grams

Cylinder Number	Ring No.	Before	After	Change
1	1	28.6642	28.6572	0.0070
	2	27.0193	27.0168	0.0025
	3	17.0194	17.0116	0.0078
2	1	28.6089	28.6008	0.0081
	2	26.7556	26.7527	0.0029
	3	16.7731	16.7650	0.0081
3	1	28.8235	28.8158	0.0077
	2	27.0089	27.0067	0.0022
	3	16.7529	16.7448	0.0081
4	1	28.6846	28.6715	0.0131
	2	27.0167	27.0143	0.0024
	3	16.9284	16.9205	0.0079
5	1	28.7220	28.7163	0.0057
	2	27.0384	27.0351	0.0033
	3	16.7623	16.7532	0.0091
6	1	28.6698	28.6632	0.0066
	2	26.9592	26.9543	0.0049
	3	16.9870	16.9779	0.0091

Ring No. 1, maximum	0.0131
Ring No. 2, maximum	0.0049
Ring No. 3, maximum	0.0091

Ring No. 1, average	0.0080
Ring No. 2, average	0.0030
Ring No. 3, average	0.0083

Connecting Rod Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	75.8145	75.7883	0.0262
1B	75.3921	75.3865	0.0056
2T	75.5546	75.5266	0.0280
2B	75.9306	75.9245	0.0061
3T	75.6658	75.6220	0.0438
3B	75.4955	75.4891	0.0064
4T	75.8352	75.7912	0.0440
4B	75.8484	75.8393	0.0091
5T	75.2890	75.2731	0.0159
5B	75.4744	75.4680	0.0064
6T	75.7134	75.6882	0.0252
6B	75.4620	75.4549	0.0071

maximum	0.0440
average	0.0187

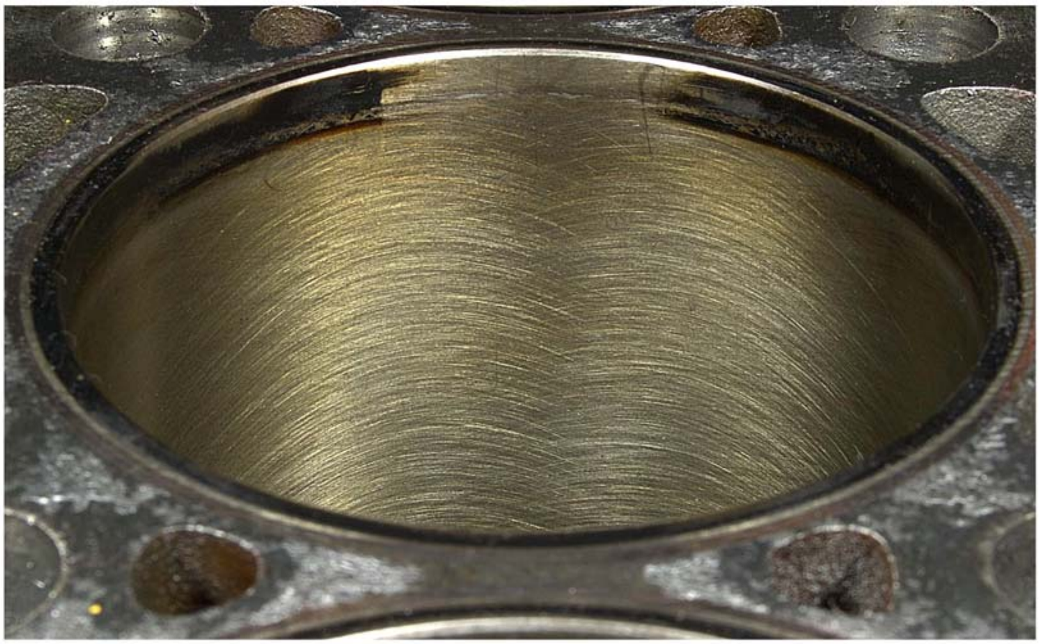
Main Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	73.2657	73.2628	0.0029
1B	81.7176	81.7138	0.0038
2T	73.8471	73.8440	0.0031
2B	81.6253	81.6218	0.0035
3T	73.2195	73.2181	0.0014
3B	81.5547	81.5524	0.0023
4T	73.7801	73.7798	0.0003
4B	81.6197	81.6169	0.0028
5T	73.2985	73.2961	0.0024
5B	81.4015	81.3980	0.0035
6T	141.2582	140.9190	0.3392
6B	81.3067	81.3039	0.0028
7T	73.3345	73.3335	0.0010
7B	81.7794	81.7753	0.0041

maximum	0.3392
average	0.0266

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Engine Block Cylinder Bore - Best Cyl. 2



Engine Block Cylinder Bore - Worst Cyl. 5

Cat C7 – Tactical Wheeled Vehicle Extended Cycle

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Piston Skirt Thrust - Best **Cyl. 2**

Piston Skirt Anti-thrust - Best **Cyl. 2**

Cat C7 – Tactical Wheeled Vehicle Extended Cycle

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Piston Skirt Thrust - Worst **Cyl. 5**

Piston Skirt Anti-thrust - Worst **Cyl. 5**

Cat C7 – Tactical Wheeled Vehicle Extended Cycle

Oil Code:	AL-27170-L AL-27755 / with FT Jet	EOT Date:	09-07-07
Test No:	FMM03100-4A	Test Hours:	420

Piston Undercrown - Best Cyl. 2

Piston Undercrown - Worst Cyl. 5

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Intake and Exhaust Valve - Best Cyl. 6

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Intake and Exhaust Valve - Worst Cyl. 1

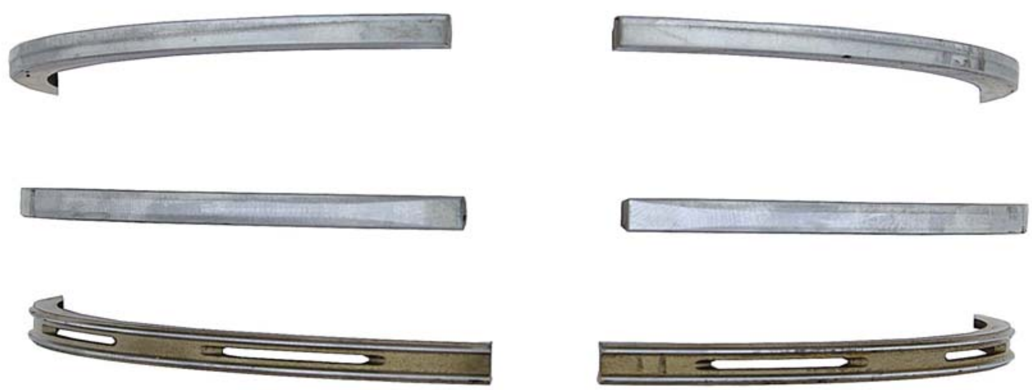
Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Crossheads - 1,2,3,4,5,6

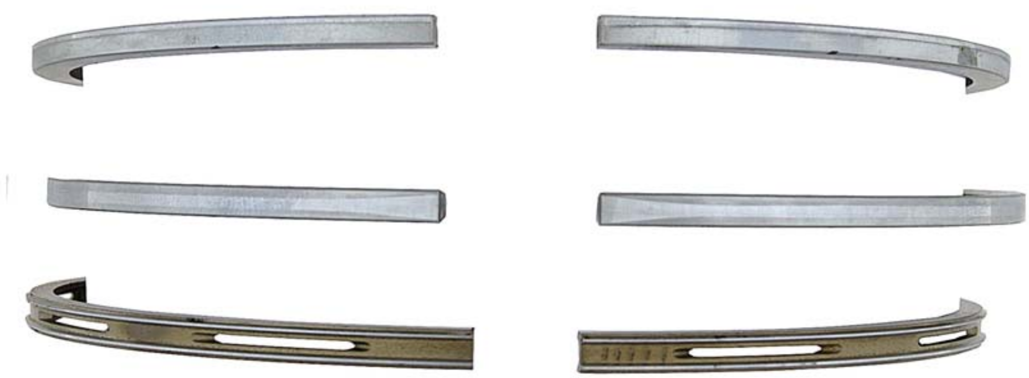
Cat C7 – Tactical Wheeled Vehicle Extended Cycle

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Piston Rings - Best Cyl. 2



Piston Rings - Worst Cyl. 5



Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Main Bearings

Cat C7 – Tactical Wheeled Vehicle Extended Cycle

Oil Code:	AL-27170-L AL-27755 / with FT Jet	**EOT Date:**	09-07-07
Test No:	FMM03100-4A	**Test Hours:**	420

Rod Bearings